

Lithium Ion Batteries and Smart Inverters to Enable Diesel-Off Operation in a High Penetration Wind-Diesel Hybrid System

A Comprehensive Report on the Kwigillingok, Alaska Emerging Energy Technology Fund Lithium Ion Battery Project

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To:

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Table of Contents

Title Page	1
Table of Content	2
Abstract	3
I. Introduction	4
A. Background	4
B. Village Growth	5
C. Funding	5
II. Method	6
A. BESS Design and Specifications	6
B. Power Electronics System Design	8
C. BESS Control Strategy	9
D. Master Control Strategy	9
E. Data Acquisition	10
III. Results	11
A. Load Profile and Wind Power Production	11
B. Diesel Off Events	13
C. Diesel Starts and Stops	15
D. BESS Performance and State of Health	15
E. Summary Statistics	17
IV. Economics	18
V. Conclusions	20
Appendix A: Specification Sheet for a Single LG Chem R800 Battery Rack	
Appendix B: One-Line Diagram of Kwig Power System	
Appendix C: One-Line Diagram of BESS Module	
Appendix D: Operating Experience/Commissioning Notes	
Appendix E: Kwigillingok Hybrid Wind-Diesel-BESS SCADA/Modelling Results	
Appendix F: Kwigillingok BESS Performance, Initial Analysis for November 2014	

Abstract

This project is a *first-of-a-kind* demonstration of autonomous Lithium Ion (Li-ion) battery storage in a remote Alaskan high penetration hybrid wind-diesel system. This field demonstration is a necessary first deployment step in understanding the benefits of integrating Li-ion batteries with wind-diesel grids. As more advanced vehicle battery technologies become available, one potential high-value application is the use of the fast recharge capabilities of these batteries in high penetration wind-diesel power systems. The Li-ion batteries, power conditioning systems, and advanced supervisory controls are combined into a Battery Energy Storage System (BESS) which maximizes fuel displacement by enabling diesel-off/wind-only operations. The project also provides valuable deployment experience, increases hybrid power system performance, and ultimately delivers the technology to enable lower energy costs for isolated communities.

I. Introduction

Stand-alone village electric power systems across the world today rely almost entirely on operation of diesel electric generators. For some time, it has been recognized that renewable sources of power, such as wind and solar PV, present promising opportunities for displacing diesel fuel and lowering the cost of energy for many of these communities.

However, the application of village scale wind and solar PV entail significant one-time expenditures. In addition to engineering, design, and integration costs, there are one-time expenditures associated with construction, distribution installation or upgrades, and mobilization of heavy equipment (such as cranes, loaders, pile drivers and barges). By their nature, smaller installations (and smaller turbines) represent higher costs per kW, lower productivity, and less energy available to meet other community energy needs (such as heating fuel displacement). Therefore, access to large, inexpensive, more productive wind and solar PV installations (which can benefit from economies of scale) facilitates profitable renewable energy installations.

Over the last ten years, considerable investments have been made in hybrid wind-diesel systems for such villages in Alaska—many of which have proven to be marginally economical. This is primarily because the renewable contributions and associated fuel displacements are restricted by the inability to fully deactivate the diesel engine generators. Integrating wind and solar into remote diesel-based power systems presents unique challenges requiring the maximization of renewable penetration while ensuring stable and cost effective electrical power service.

In simple low and medium penetration wind-diesel systems, the diesel generators run continuously. The wind energy reduces the overall load on the diesels, which make up for the deficit between the wind power and the primary load. As the wind capacity increases, the energy contribution of the wind is restricted by the minimum loading requirements of the diesel generators. Similarly, the fuel savings in these systems is limited by the poor part-load efficiency of the diesel generator sets. The ability to turn the diesel engines off and supply the primary load with wind power alone could generate substantial fuel savings and lead to larger, more cost-effective wind installations.

The present work is a “first of a kind” in-village demonstration project, which uses modular inverter systems and high performance vehicle-format Lithium ion (Li-ion) batteries to provide short term ($< 1/2$ hour) energy storage in an existing rural village wind farm. This report describes the system installation, operation, and performance of the Li-ion battery energy storage (BESS) system in the active village wind diesel system of Kwigillingok, AK, in fulfillment of grant requirements. It also provides a fundamental basis for understanding the role that Li-ion battery storage can play in reducing energy costs in rural Alaska. Due to the success of this project, the authors feel that there is potential for widespread application of this technology throughout the state.

A. Background

Kwigillingok (Kwig) is a Yupik village of 400 residents located on the lower Kuskokwim River, approximately 85 airmiles southwest of Bethel (Figure 1). Kwig has no connection to any road systems or electrical transmission networks.

Kwig’s power plant consists of four John Deere generator sets: two 6090 industrial engines (rated at 250 kW), one JD 6081 (180 kW rating), and one JD 4045 (90 kW). The village has an estimated 6.5 miles of electrical distribution.

In late 2012, five 95 kW Windmatic, 17s wind turbines, were integrated into Kwig's power grid. The wind turbines are fixed pitch, three-bladed wind turbines. The generators are induction type asynchronous generators fitted with variable speed drives. During strong wind events the wind system can provide more electrical energy than the village requires for the primary load. A fast-acting load regulating boiler (LRB) and 25 electric thermal storage (ETS) units have been integrated into the power system to absorb any surplus wind energy and maintain power system balance.

B. Village Growth

At the outset of this project (2012) the annual community electrical demand was 1,094,610 kWhrs. It was estimated that the load would grow at no more than 3% per year. Due to improvements to the water and sewer systems, new housing, a new church, a new post office, and a doubling of the size of the school, electric load demand has increased over 44% since 2012 (Table I).

Table I. Kwigillingok Electrical Load Growth

Year	Total Electrical Generation (kWh)	Population	Diesel Generation (kWh)	Non-Diesel Generation (kWh)	Average Load (kW)	Peak Load (kW)
2012	1,094,610	321	1,094,610	0	125	200
2013	1,185,025	342	1,125,730	59295	135.3	216
2014	1,318,782	317	1,038,264	280518	150.3	241
2015	1,584,065	349	1,157,736	426329	180.8	289

Additionally, the increase in average electrical load demand has grown from 135 kW (in 2013) to 150 kW (in 2014) and 180 kW in 2015. This increase in average load is accompanied by even more significant increases in the daily peak loads ranging from a high of 187 kW (in 2012) to nearly 285 kW (in 2014) to over 300 kW today. As will be shown, this increase in village load (as well as the loss of one wind turbine due to a mechanical problem) has negatively impacted the opportunity for periods of diesel-off operation. Nonetheless, a success demonstration has been made and continues to deliver significant fuel savings to the residents of Kwig.

C. Funding

Funding for the project was provided by the Emerging Energy Technology Fund (EETF)—a program sponsored by the Alaska Energy Authority (AEA) and the Denali Commission. EETF expressed interest in this project because energy storage (especially Li-ion BESS) could potentially have widespread application, enabling an increase in wind energy in the remote hybrid power market. EETF support has been provided as a catalyst to reduce the technical and financial risks involved with advancing promising technologies. The primary innovation demonstrated in this project is the ability to use a small amount of energy storage to maximum available wind power, reduce diesel fuel usage, and enable reliable diesel-off/wind-only operation.



Figure 1 - Kwigillingok is a coastal village located 85 air miles southwest of Bethel, AK.

II. Method

The scope of the present work includes integration of a stand-alone BESS module with existing wind and diesel generation in the village of Kwig. The existing hybrid system is equipped with a diesel plant, a wind farm, a distributed family of ETS stoves (secondary loads), a Load Regulating Boiler (LRB), and SCADA (Supervisory Control and Data Acquisition) system (Figure 2). For this integration, changes were necessarily made to the master controller program, which will be discussed in further detail in this section.

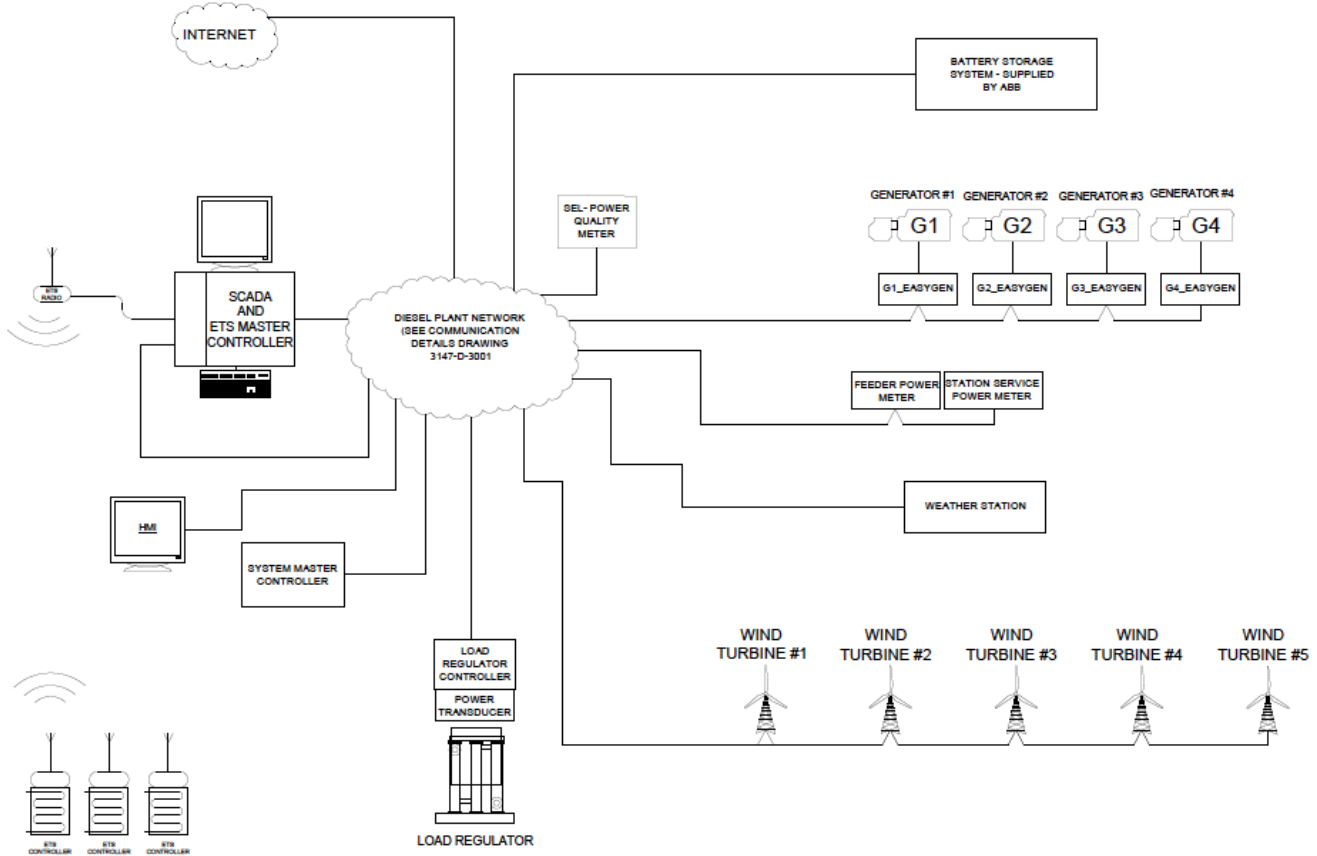


Figure 2 – Schematic of the Kwig power system showing integration of the BESS with existing wind and diesel power systems.

A. BESS Design and Specifications

The Kwig BESS module is comprised of a battery rack, Battery Management System (BMS), power electronics, Human Machine Interface (HMI), and a 3-phase 60 Hz 480 V / 12,470 V AC dry type step-up transformer, all contained within a small, modular housing (Figure 3). The BESS is directly connected to the Kwigillingok electrical distribution grid at a remote location (Figure 4). This is purposely not a controlled testing environment, but instead an actual in-field application of the technology. The purpose of the BESS is to provide voltage stability, frequency regulation, and energy bridging to support diesel-off/wind-only operations on an active isolated power grid.

Selection and design of the battery and its associated components require consideration of the storage capacity requirements, charge/discharge ratings, and allowable number of cycles for the anticipated life

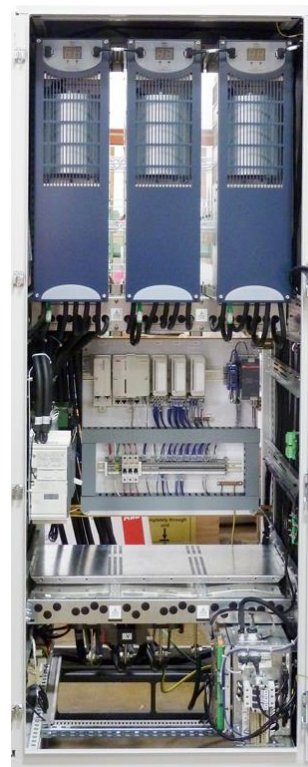
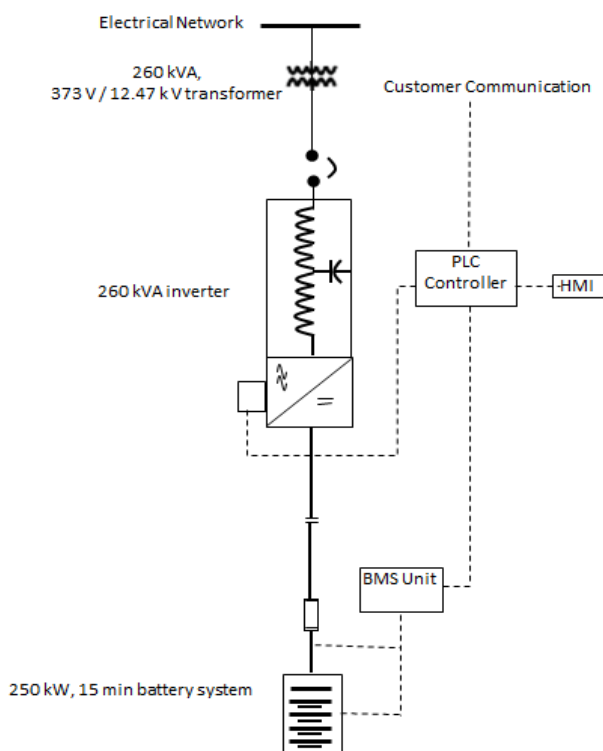
2) Discharge Rating - A 65 kWhr BESS with a discharge rating of C1 would provide 65 kW of power for 1 hour. The LG Chem batteries in Kwig have a C ¼ rating, which means the batteries can be discharged in ¼ the time. Thus, a 65kWhr BESS can be discharged at 4 times 65 kW (260 kW) and meet the ‘250 kW for 15 minutes’ requirement. Ultimately, LG Chem offered to provide 135 kWhrs of battery energy storage at a discount to participate in this demonstration. IES graciously accepted the offer and chose the larger battery.

3) Charge Rating - The Li-ion batteries can be recharged at C2, or twice their capacity in an hour. In practice, full recharging in 30 minutes does not occur, as charging only occurs when surplus wind energy is available. However, the ability of the Li-ion batteries to handle large currents either in charge or discharge mode is critical for grid frequency regulation.

4) Battery Life - BESS performance is guaranteed by the manufacturer for at least five years, assuming no more than 3000 full-depth charge/discharge cycles. It is anticipated that the battery system, when cycled between 75% and 25%, will last seven to ten years, based on manufacturer estimates.

B. Power Electronics System Design

The power electronics system provides the AC to DC and DC to AC conversion interface with the DC battery and facilitate charging and discharging. It is composed of three ABB PCS100² “Power



Conditioning System” units (rated to 800 V each, 260 kVA total capacity), AC circuit breakers, DC contactors and a local control panel, all housed within a common enclosure cabinet. The inverter controller was configured to interface with the LG Chem BMS, which manages charge and discharge of the battery from 588 VDC (discharged) to 814 VDC (charged).

Figure 6 (left) provides a single line drawing and panel photograph of the power electronics cabinet. The BESS power electronics are controlled

Figure 6 - (a) Schematic and (b) photo of the power electronics cabinet.

² ABB networks their small, modular PCSs to their energy storage system to achieve the same power rating as a single, larger converter. This modularized power electronic strategy has the advantage of redundancy (should one unit fail not all capacity is lost) and scalability (to meet growing needs) in that additional modules may be added as the system grows. It also lends itself to field repairs, as most replacement components can be delivered to a remote site via single engine aircraft.

by a dedicated Master Control PLC (Programmable Logic Controller) through an interactive HMI screen. The PLC coordinates the power conditioning modules, controls energy flows into and out of the battery, and serves as the primary interface to the LG Battery Management System (BMS). The BESS HMI is used for local power electronics control, local system monitoring, parameter selection, alarm indication, and other advanced functions. A diagram of the power electronics system functionality is provided in Figure 7.

Figure 7 – Schematic of the power electronics energy conversion system

Initially, it was anticipated that two distinct wind-diesel-battery control strategies, similar to those used for hybrid electric vehicles, might be possible. These two control strategies were described as: (1) Dynamic Charge Depletion (DCD) and (2) Controlled Charge Sustenance (CCS). The DCD control mode is an operational mode in which the load is met by energy stored in the battery and the combustion engine generator recharges them. CCS mode blends the operation of the various system components, in parallel, using both the engine and the battery to meet the load. It was soon recognized that a simpler, system-wide control scheme could be made to reliably maximize the use of excess wind and effectively manage BESS state-of-charge.

Automatic dispatch and overall control of the wind-diesel-BESS system is provided by the System Master Controller (SMC). This control infrastructure was installed with the construction of the original wind farm and was modified to include the BESS and associated peripherals. The SMC's primary objective is to ensure that the village load is met with an appropriate mix of wind power and available diesel reserve with no interruptions to service—an intricate task.

The Kwig SMC operating modes include:

2. Wind Diesel-Low: Wind turbines are available and running if wind power is sufficient to provide positive energy to the village grid. This is a low penetration operating mode, in which the diesel generator is still controlling frequency and fuel use is offset by wind generation.
3. Wind Diesel-High: This is a medium penetration operating mode, where the diesel is driven down to its Minimum Load Set-point (MLS; usually 25% to 30% of rated capacity) and the Load Regulating Boiler (LRB) assumes responsibility for frequency control.
4. BESS Charging: Diesel generators and wind turbines are providing power. The diesel generator is providing voltage control, while the LRB regulates frequency by absorbing excess real power. After the village load is accommodated, the excess energy goes to charging the BESS.
5. BESS Discharge Allowed: In this mode, the wind resource is greater than it is in Wind Diesel Mode. Diesel generators provide a steady minimum kW and kVar to the village grid. The BESS controls frequency and voltage while also providing the positive and negative energy to balance the village load and the wind power.
6. Diesels Off: Wind is the only source of real power and all diesels are shut down. The BESS provides the positive and negative energy to balance the village load with the strong, variable wind power and is solely responsible for frequency and voltage regulation. The LRB becomes the heat source to the power plant, keeping the diesel generators warm and ready. The ETS units³ are available to absorb any surplus wind energy not required by the electrical load, the battery, or the load regulating boiler. Currently, due to electrical load growth and diminished wind farm capacity, there is insufficient surplus wind energy to provide an appreciable amount of supplemental ETS heating.

The SMC ensures that the electrical load is always met. The control system monitors wind, load and battery State of Charge (SOC). When wind alone is sufficient to meet the load (and the battery reaches 80% SOC), the diesels are shut down. The energy stored in batteries covers sudden drops in wind power and provides supply continuity when transitioning between modes. The nature of wind events is such that the wind power is either rising, falling or stable, usually for hours at a time. In this project, a diesel is started before the energy storage is depleted and is then blended into the system.

E. Data Acquisition

A data collection computer was located at the power house and connected via fiber optic cable to the BESS module (through an integrated web server). The computer collects data from the wind-diesel SCADA, the power electronics system, a Power Quality Meter (PQM) at the BESS module, and a weather station at the power plant. Data is housed in a structured database.

The data used in the results section of this report were provided to the Alaska Center for Energy and Power (ACEP) on November 21st of 2016. A comprehensive analysis was also conducted by IES and will be presented and discussed in III.

³ Note that ETS units are also utilized in Wind Diesel-High and BESS Discharge Allowed modes.

III. Results

Nearly one year's worth of data in one-minute intervals were analyzed and are summarized here. The dates range from March 6th, 2015 to February 16th, 2016 (347 days). Several example diesel-off events will be presented and discussed, as well as the long-term observations regarding frequency control, diesel starts/stops, and net energy delivered.

A. Load Profile and Wind Power Production

Figure 8 shows the probabilistic nature of generated wind power and primary consumer demand for Kwigillingok. During the 347-day observed period, the primary village load fluctuated between about 100 kW and 250 kW, with some events outside this range. Wind was not present for 30% of this time, but

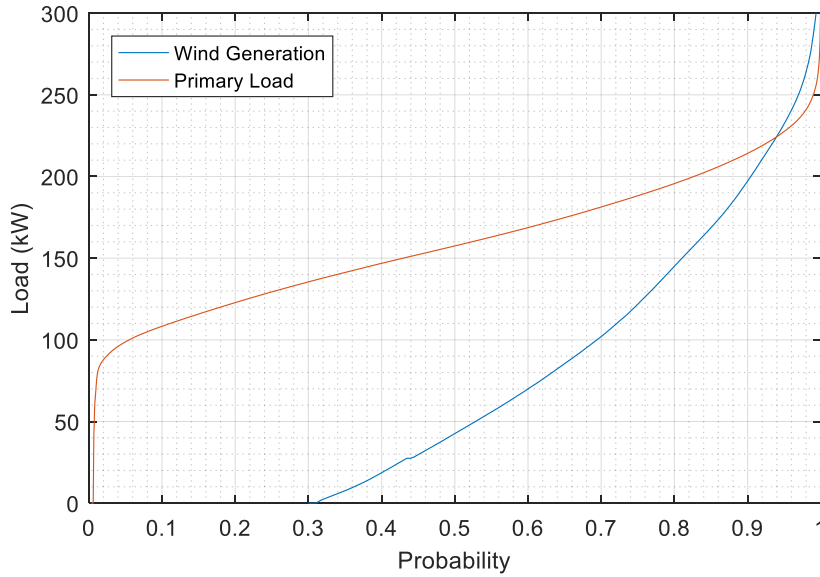


Figure 8 - Cumulative distribution of wind generation and primary load.

peaked out at around 300 kW at its maximum. The relative areas within the intersection of these curves illustrate the potential wind power penetration of grid demand, assuming random variation. However, wind power and primary load are not entirely random. Seasonal and diurnal patterns are present and can be seen in the measured data.

Figure 9 shows both the generated wind power and primary consumer load profiles by hour of the day and day of the year. (On a 24-hour clock and 365-day year

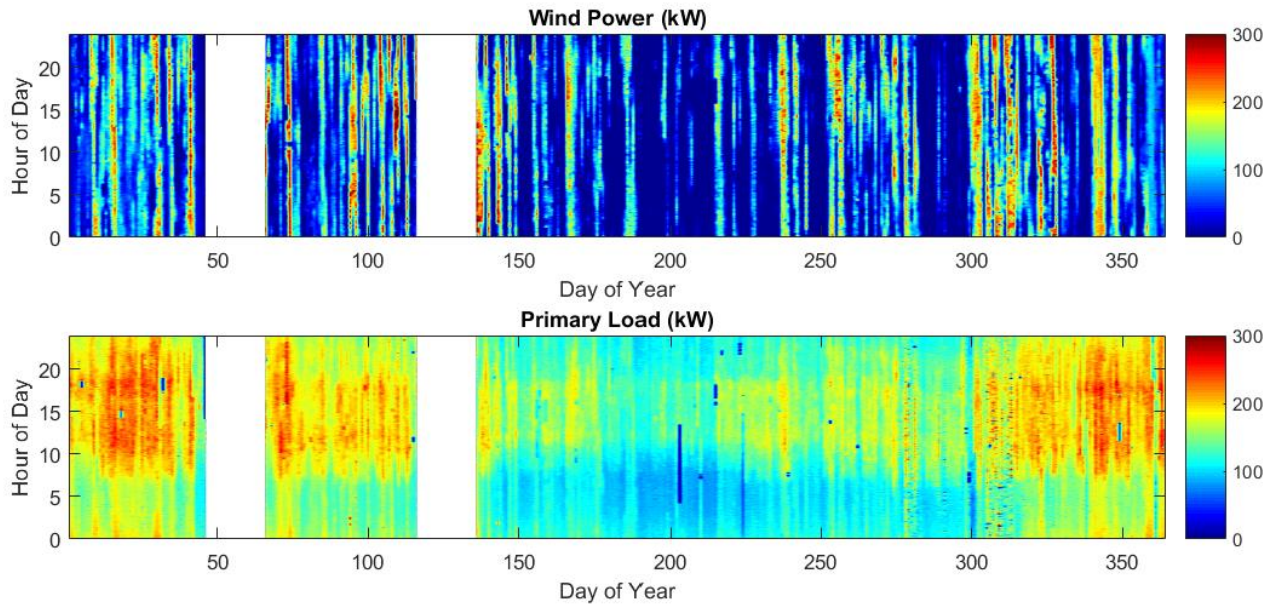


Figure 9 – Total generated wnd power and primary load profiles by hour of day and day of year.

from January 1st to December 31st. (White regions represent missing data.) Wind power does not appear to vary by time of day, but is stronger and more prevalent during the winter months. Large lulls can be seen during summer, where measurable wind power is absent for more than a week at a time. Primary grid demand correlates strongly with time of day and day of year. Power use peaks at hour 15 (3:00 PM) and bottoms out at around hour 5 (5:00 AM) with a stronger presence during winter months.

Data from Nov and Dec of 2015 show the power output of each Wind Turbine Generator (WTG)⁴ versus the wind speed measured at their respective hubs (Figure 10).

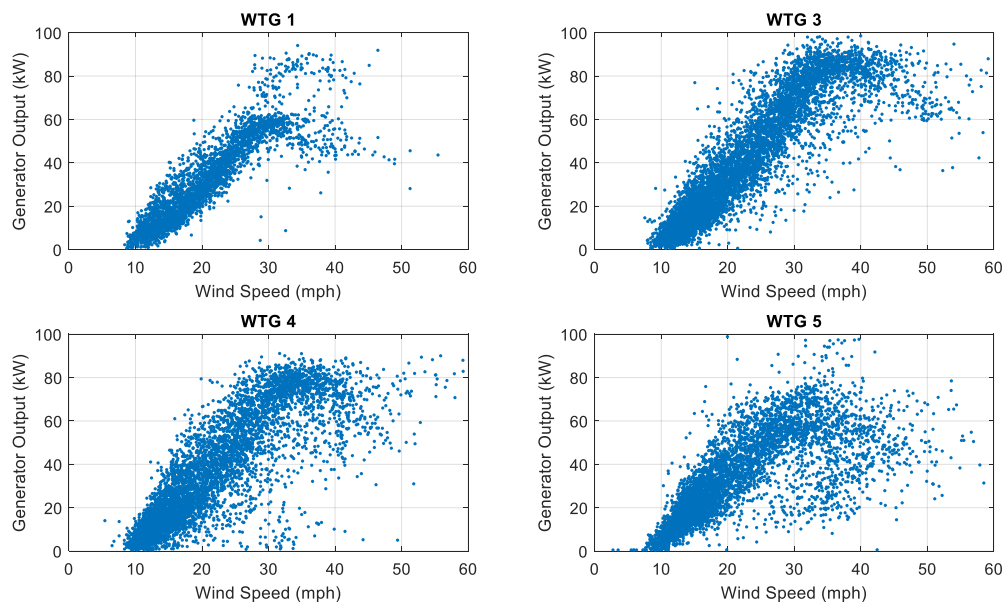


Figure 10 - Measured wind turbine power curves, Nov and Dec 2015 (10-minute avg). WTG2 is not functional during this time.

Since its installation, the Battery Energy Storage System has performed as designed. However, a number of issues related to utility operations have prevented full application of the wind battery system. A few of these issues include:

1. A wind farm feeder failure in spring of 2014 caused nearly two months of wind farm down time.
2. The construction of a new school, which went online in September 2014, brought with it several electrical service issues. These issues were finally resolved in October 2014 when soft-start VFDs were installed on the offending pump motors.
3. Several days of down time occurred during April of 2015 when the SCADA experience a total failure and had to be replaced with a new unit.
4. Various utility operational issues prevented the collection of 12 months of contiguous BESS data and further delayed progress of the project.

Such issues have resulted in erratic wind power production over the course of the last few years (see Figure 11), though the BESS system itself is rarely (if ever) the cause.

⁴ In January of 2014, a gear box casing failure rendered Wind Turbine Generator (WTG) #2 inoperable. Since that time, the village has been running with only four wind turbines.

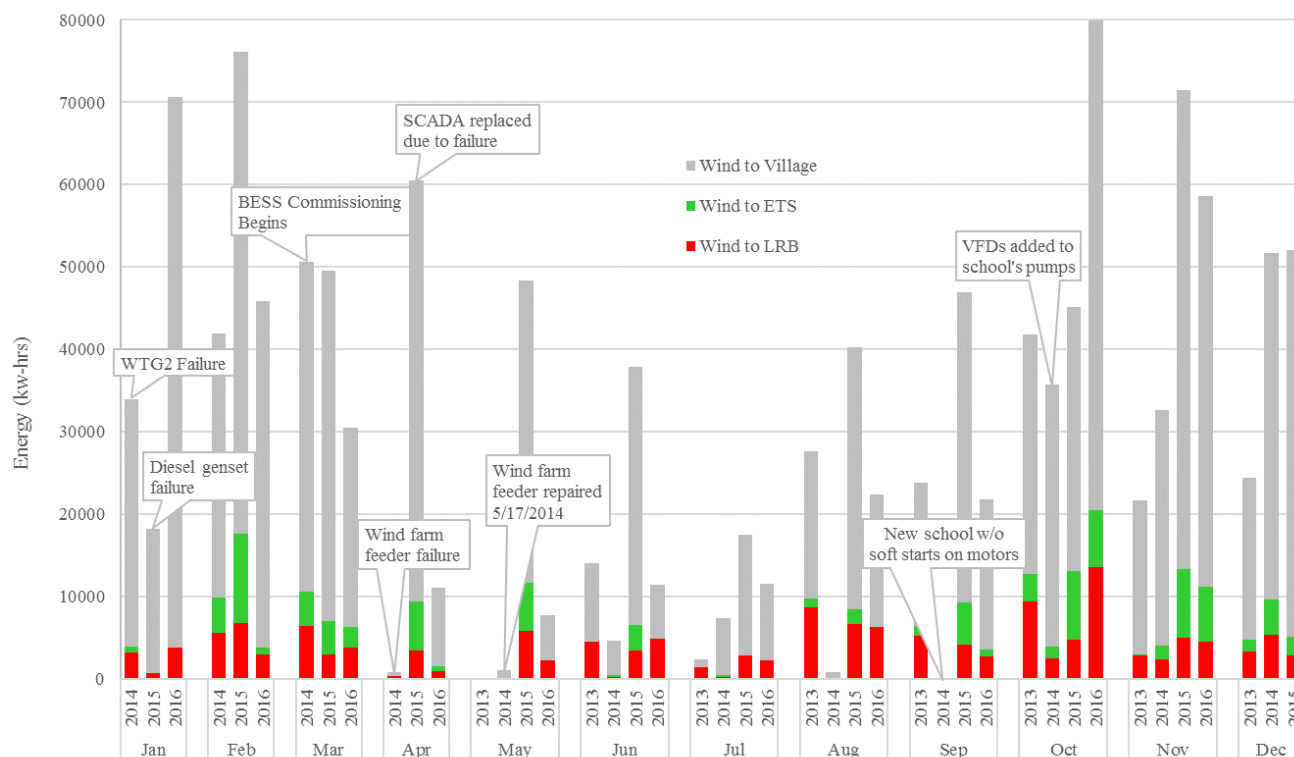


Figure 11 – Wind power delivered to the village, the ETS, and the LRB, by month and year.

B. Diesel Off Events

The system in Kwig has been successfully transitioning in and out of diesel off periods autonomously since commissioning, in March 2014. The following is a snapshot at two such events, followed by a summary of the system performance over the course of an entire year.

Figure 12 shows an example of a long, but typical wind event, which lasts approximately 34 hours. The primary load fluctuates between 110 kW and 275 kW throughout the event and the diesel generator is off for the greater portion of this time. As wind picks up and diesel output is reduced, the diesel generator is held at the minimum load set-point (MLS) of 65 kW while the LRB steps in to control frequency (for just under 2 hours). With a sufficiently charged battery and an increasing amount of wind, the diesel is disconnected and the system enters Wind Only mode. There are three events during this period where the diesel comes back on to its MLS—for 21 minutes, 49 minutes, and 41 minutes. When the battery reaches a sufficient state of charge (76%) the ETS devices begin absorbing surplus wind energy. Frequency control during the period of diesel off is superb, as can be seen in Figure 12(c). When the deficit between the wind power availability and the primary demand of the load becomes too high, the system controller brings the diesel generator back online to prepare for the end of the wind event.

Another similar, but longer wind event occurred between the dates of September 12th and September 15th, 2015. This resulted in a diesel off event more than 45 hours in duration (Figure 13). The total wind power remains above 100 kW for the duration of the event, allowing the BESS to assume control of frequency. The BESS can be seen fluctuating between a 37% and 73% SOC as wind power ebbs and flows.



Figure 12 - A typical wind episode showing power (a) generation, (b) consumption and (c) frequency. Diesel off (x) and diesel on (o) events are shown, as well as BESS State of Charge.

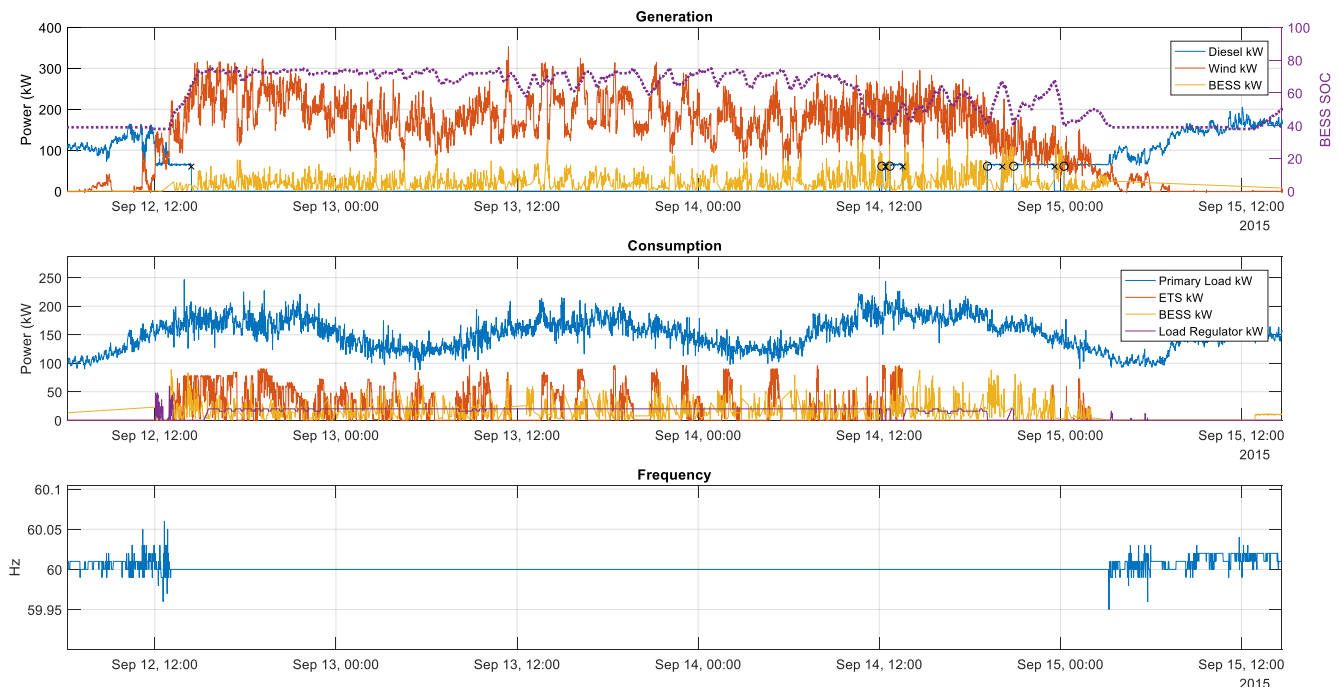


Figure 13 - The longest diesel-off event recorded during the 347-day observation period lasted 45 hours and occurred in September of 2015. During this time, the entire consumer load was powered by wind while the excess charged the ETS.

C. Diesel Starts and Stops

A key objective of the SMC is minimization of diesel starts and stops. A gross analysis of diesel-on/diesel-off events was performed to determine the average switching frequency. The SMC program is designed to ensure that the diesel engine does not shut down until sufficient wind power is present and the BESS is fully charged, but it is also designed to bring the diesel back online if wind power unexpectedly drops off. It is undesirable to be switching the diesel on and off quickly, as such short on/off durations can significantly reduce the life of the equipment.

In the 347 days analyzed, there were 335 diesel-off events. (Logically, there were also 335 diesel-on events.) This amounts to an average of less than one on/off cycle per day. Of course, these events are not distributed evenly throughout the analysis period—they correlate heavily with the presence of wind events. Figure 14 shows the cumulative distribution of these events in three different time windows: (a) events lasting less than 12 hours, (b) less than 3 days, and (c) less than 10 days. For example, it can be seen from the mark on the first subplot that there were 200 diesel-on events lasting less than 5 hours. Other observations include:

- The longest diesel-off event lasted just over 45 hours
- The longest period of diesel-on lasted more than 240 hours
- There were 300 diesel-off events less than 12 hours in duration
- There were 10 diesel-off events lasting 20 hours or more

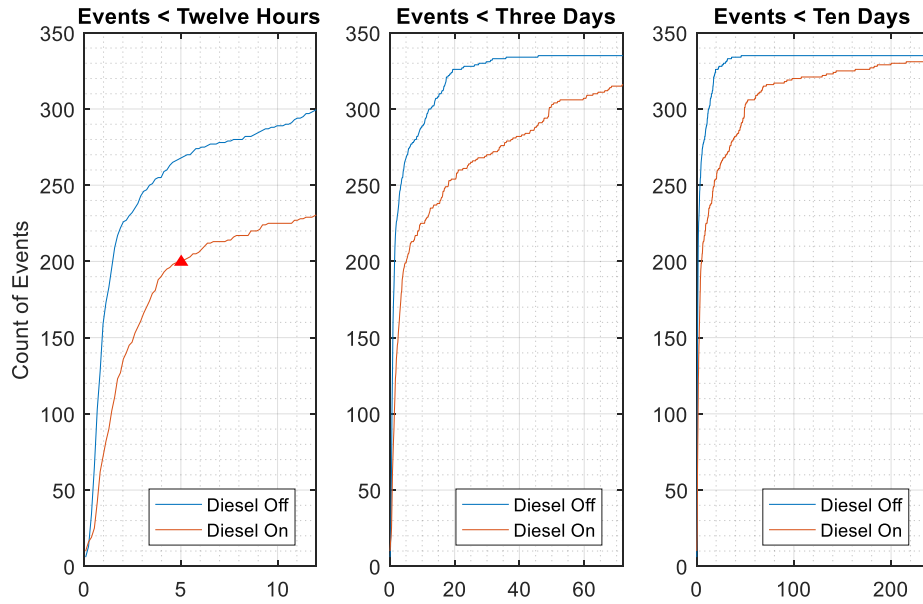


Figure 14 - Duration of diesel-on and diesel-off events for the 347-day analysis period. (x axis hours)

D. BESS Performance and State of Health

The life and overall health of the battery is a strong function of the number of charge cycles. Battery cycles can be measured using the following formula

$$N = \sum_{i=2}^n \frac{|SOC_i - SOC_{i-1}|}{200}$$

where N is the number of charge cycles, i is the index of the digitally-sampled SOC vector (measured in percent), SOC is the state of charge, and n is the last index of the sample period. (As an example, a full charge and discharge from 0% to 100% and back to 0% would constitute one cycle.) The total number of cycles calculated for the sample period was 123.1, or an average of 0.35 cycles per day. If the battery lasts as long as warranted by the manufacturer (3000 cycles), it would have a life of 23 years at the current cycle rate. However, it is not anticipated that the BESS will perform at its current level for more than ten years.

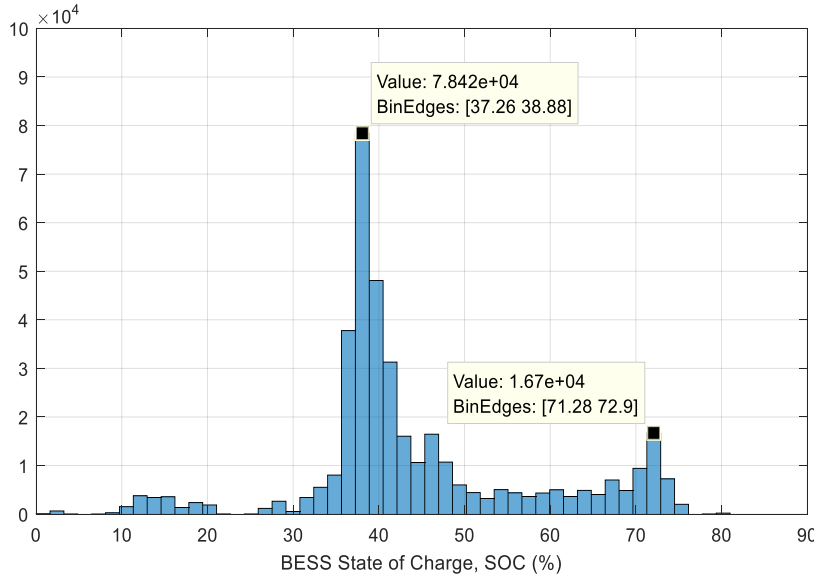


Figure 15 - BESS State of Charge histogram. Peaks show programmed minimum and maximum charge limits.

The BESS also reports and records SOC. The histogram (Figure 15) for the entire sample period (347 days) shows the SOC primarily fluctuating between two values (37% and 73%). These limits are set to maximize the life of the batteries. The peak at 37% is higher, indicating that the system spends more time closer to its lower charge limit than it does near the upper.

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When in diesel-off mode, the BESS is responsible for system frequency regulation. Power quality measurements confirm that the BESS provides superior frequency control. When the system is in wind-only mode, frequency control is as good or better than it is when either the diesel or the LRB are in control. (Figure 16).

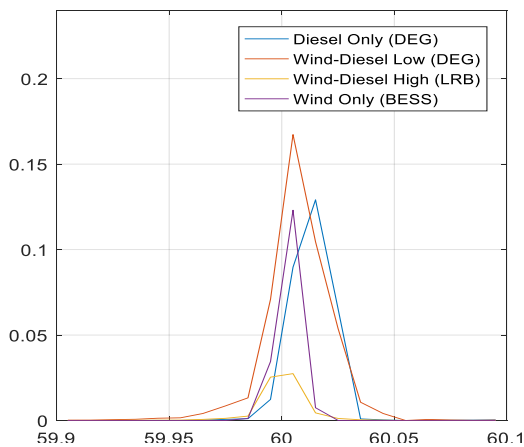


Figure 16 – Frequency regulation probability density for the 347-day sample period. BESS frequency control is exceptional.

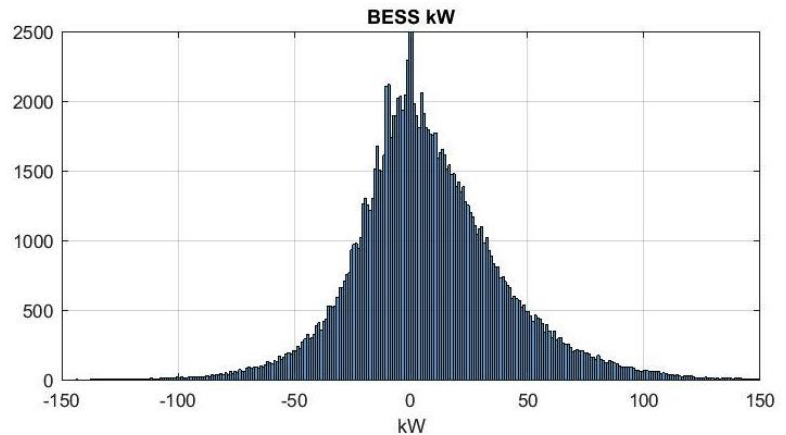


Figure 17 – BESS power histogram. Positive kW indicates power flow out of the BESS (discharge), negative values indicate charging current (power leaving the BESS).

E. Summary Statistics

During the 347-day period analyzed, the contribution to generation by the diesel plant was 57.3%, while the wind contribution was 40.2%. Since the BESS is only responsible for facilitating wind-only and not large enough to deliver long-term power, it's contribution is only 2.5%. Since the BESS is not an energy source, but a storage buffer, this 2.5% can be grouped with the 40.2% wind contribution for a total of 42.7%.

The average number of diesel starts per day was 0.96, with the same number of stops. All diesels were off 16.9% of the time—equivalent to about 1480 hours per year.

IV. Economics

The primary economic objective of the BESS is to remove the minimum load restrictions on the diesel plants and increase wind penetration. When the MLS on the diesel is removed, the value of wind increases from the marginal cost of displaced diesel fuel to the full cost of diesel generation. Therefore, the main value of the battery is equivalent to the savings associated with operating in diesel-off. For a comparison, the costs associated with operating a John Deere 6090 are shown here, in Tables II-V.

Table II. John Deere 6090 Diesel, Annual Maintenance Cost Summary (Engine Only)

	Parts	Labor	Estimated Cost
Change engine oil & replace filters (18 @ 500 hrs)	\$3690	\$1350	\$ 5040
Replace fuel filters (8ea)	\$ 1150	\$ 400	\$ 1540
Clean crankcase vent tube.	\$ 132	\$ 100	\$ 232
Replace air cleaner elements (8)	\$ 780	\$ 200	\$ 980
Check exhaust system, EGR	\$ 756	\$ 200	\$ 956
Check and service engine cooling system	\$ 600	\$ 450	\$ 1050
Replace engine coolant (1)	\$ 2556	\$ 800	\$ 3356
Replace starting batteries (.5)	\$ 280	\$ 100	\$ 380
Scheduled inspection of turbocharger, electrical, etc.		\$ 4560	\$ 4560
Adjust Valve Clearance	\$ 35	\$ 650	\$ 692
Summary estimate annual diesel maintenance cost			\$ 18,786
Estimated Hourly maintenance cost			\$ 2.14

Table III. John Deere 6090 Diesel Engine Capital Cost of Ownership Estimate

Continuous prime power operation, replace or rebuild @ 14,000 to 17,000 hour			
	Parts	Labor	Estimated Cost
6090 long block replacement (17,000 hours)	\$ 50,860	\$ 26,600	\$ 77,460
Annual replacement costs			\$ 39,914
Estimated hourly engine capital cost			\$ 4.56

Table IV. John Deere 6090 TOTAL Annual Operating Cost Estimate

		gallons	\$ 3.00/gal	\$ 3.50/gal	\$ 4.00/gal	\$ 5.00/gal
1,200,000 kWh's generated	Fuel Efficiency					
	12.5 kWh/gal	96,000	\$288,000	\$336,000	\$384,000	\$ 480,000
Hourly Fuel cost			\$ 32.88	\$ 38.36	\$ 43.84	\$ 54.79
Yearly O&M			\$ 58,692	\$ 58,692	\$58,692	\$ 58,692
Hourly O&M			\$ 6.70	\$ 6.70	\$ 6.70	\$ 6.70
Total Estimated Operating Cost			\$ 346,692	\$ 394,692	\$ 442,692	\$ 538,692
Estimated Cost per kWh			\$0.29	\$ 0.33	\$0. 37	\$0 .45

Table V. John Deere 6090 Cost of Operating at Minimum Operating Set Point for 2600 hours Annually

		Gallons/hour	\$ 3.00/gal	\$ 3.50/gal	\$ 4.00/gal	\$ 5.00/gal
@ 65 kWh	Ave Fuel Efficiency					
65 kW	9.3 kWh/gal	6.5-7.5				
Hourly Fuel cost			\$ 21.00	\$ 24.50	\$ 28.00	\$ 35.00
Hourly O&M			\$ 6.70	\$ 6.70	\$ 6.70	\$ 6.70
Total Estimated Operating Cost			\$ 27.70	\$ 31.20	\$ 34.70	\$ 41.70
Estimated Cost per kWh			\$.43	\$.48	\$.53	\$.64
Annual Value of 2600 hours of diesel off operations						
			\$ 72,020	\$ 81,120	\$ 90,220	\$ 108,420

The present cost structure of this demonstration is based on the current state of development and practice, with the batteries making up less than 15% of the total project cost. Since the technology is developing rapidly, cost reductions and performance improvements of 25% or more can be expected. Similarly, the economic performance of the system is highly dependent on the cost of fuel. At the current cost of fuel in Kwigillingok (\$4.10 per gallon) and a future capital cost of \$750,000, annual operations and maintenance costs of \$2,400, and a \$90,000 battery replacement cost every 7 years, the project would have a net present value of \$161,683 over a twenty-year time horizon (and assuming 2600 hours of diesel off operations). The NPV is highly sensitive to the cost of diesel fuel, which, should it rise to \$5.00 per gallon, would be \$346,777. Similarly, if the cost of diesel fuel were to fall to \$3.50 / gallon, the NPV would fall to \$38,287, which is nearly the break-even point for this investment.

The economic benefit demonstrated by this project ultimately comes from the high energy transfer rates and high cycling capabilities of the LiOn batteries.

Table VI. Financial Investment Assumptions

2015 PCE reported cost of fuel	\$ 4.10/gal
Installed capital cost:	\$ 750,000
Annual Operations and Maintenance costs:	\$ 2,400
Battery replacement costs, 7 year intervals	\$ 93,000
Utility interest rate	6%

V. Conclusions

This project has successfully demonstrated the performance of a Li-ion battery system to enable diesel-off operations on a functioning high penetration wind-diesel grid. Overall, the system is performing as expected, though the life of the battery is yet to be determined. The strength of the system is not in the use of the battery's storage capacity as a generation source. Rather, the battery is a dynamic stabilization source, with a small amount of energy storage, which enables the wind power to meet the primary load requirements with no input from the diesels. Additionally, the major components of the BESS (including the Li-ion battery racks, the power electronics/conditioning system, and the supervisory controls) have proven to be highly reliable.

During the 347-day demonstration period, the system operated for 1404 hours on wind only. At this rate, annual diesel off hours would amount to 1476. While, initially, the system was estimated to provide 2600 hours of diesel operations, circumstances related to the utility distribution and diesel plant operations, the battery was only able to operate approximately 60% of the time during the test period. Whenever the battery system was enabled it performed as designed, automatically shutting down the diesels when the wind power was equal to supply the primary electric load. Modeling studies provided a target of 2600 hrs of diesel off operations, and had the battery system been allowed to operate as designed, this target would likely have been met.

The BESS installation in Kwigillingok is a pioneer *first-of-a-kind* demonstration. The project was expensive to execute and met a host of *first-of-a-kind* application and integration issues, as well as remote project deployment problems. Based on what has been learned, this project is likely to become the first of many LiOn battery projects for village renewable applications and will lead to the establishment of a new standard in wind diesel performance. Further cost and performance improvements in LiOn battery technology, increased deployment, and additional operating experience can be expected to trigger widespread adoption of this technology.

Appendices

Appendix A: Specification Sheet for a Single LG Chem R800 battery rack

Note this project has 3 racks, for a total of 135 kWh

Nominal Characteristics	LG Chem Rack (R800)
Voltage	725 V
Capacity (1C)	60 Ah
Nominal Energy	45kWh
Physical Characteristics	
Width	600 mm
Depth	650 mm
Height	<u>2100 mm</u>
Weight	<u>700 kg</u>
Electrical Characteristics	
Voltage Range	<u>580 to 820 V</u>
Maximum C Rate	4
Cell Series/Parallel Configuration	<u>4P196S</u> (Fourteen 4P14S modules in series)
Operating Conditions	
Battery Management System (BMS)	Rack BMS
DC Protection	Circuit breaker, contactor, relay, voltage sensor
Cooling Strategy	Air-cooled



Front View



Side View

LG Chem Battery Module (M4860)	
Nominal Characteristics	
Voltage	51.8 V
Capacity (1C)	63.2 Ah
Energy (1C)	3.21 kWh
Physical Characteristics	
Width (compatible with 19" rack)	445 mm without mounting (17.5")
Depth	550 mm (21.7")
Height	122 mm (4.8")
Weight	35 kg (77 lbs.)

Note: The chart above shows the Amp/hour capacity of one LG rack a with a 1C charge rate. The rack can work with a maximum of 240 Amp.

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45
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12.47KV, 3ø
60Hz

CUSTOMER SUPPLY

ABB SUPPLY

E-HOUSE

STEP-UP XFMR
260KVA
12.47KV/374V

PCS100 ENCLOSURE

600A

INVERTER
260KVA

GMD

HMI

PCS100 INVERTER CONTROLLER

CONTROL SUBPLATE

UPS

AUX. XFMR
30KVA
374/120VAC

HVAC & ENCLOSURE LOADS

120V
5A
AUX.

1.5KVA

UPS

500A

V-XDCR
0-1200VDC

4-20mA

BMS CONTROLLER

BATTERY RACK 1

BATTERY RACK 2

BATTERY RACK 3

DESIGN

SINGLE LINE DIAGRAM
PCS SYSTEM FOR DES

06-10-13

ABB Inc.

ABB

ABB Inc.

DES - 70

06/13

Appendix D: Operating Experience/Commissioning Notes

Project highlights:

EETF award: Fall 2012, Funds available, March 2013.

Arrival BESS in Kwigillingok, October 2013.

BESS installation: February 2014.

BESS commissioning: April 2014.

It is estimated that the BESS has been disabled either locally or remotely 40% of the primary test period. Distribution failures and an unreliable diesel plant account for approximately 180 days of disabled BESS. The primary test period was April, 2014 through April 2015. Periods of restricted BESS operations occurred from June 2014 thru October 2014, and again in January 2015. Restricted operations occur when the BESS is operational with necessary monitoring from operators to manually select the diesel gensets after wind events. This is due to unreliable gensets. A load dependent stop start autonomous control only works with a reliable properly sized gensets.

Battery Energy Storage System (BESS) events:

2012 -2013

- Fall 2012, AEA EETF award selection,
- January, 2013, grant agreement AEA/ACEP
- March 2013, Funds available for procurement of long lead time items: inverter, battery, transformer, and modular housing unit.
- Last barge for Kwig leaves Anchorage, August 17, 2013.
- Factory test of the battery / inverter was not possible due to the barge schedule. The batteries were shipped separately from module and arrived in Anchorage to be loaded in the module for barging.
- Northland barge from Anchorage to Kwigillingok departs with anticipated arrival September 23.
- September a fall storm causes wide spread flooding in Kwig. Module site location reconsidered due to flooding potential.
- A new location is chosen for the BESS one mile up from the barge landing. A rudimentary road only passable for heavy equipment after freeze up connects the barge landing and the new BESS site.
- Initial Site preparation work begins. Including the foundation infrastructure, grounding ring ,and three Phase electrical tie in.
- Fall storm cycle in Kuskokwim delta continues. BESS delivery by barge, postponed until early October no exact date. Crew on standby in Kwig.
- October the barge arrives in Kwig at midnight & off loads BESS unit. The Village loader has mechanical problems and unable to lift the BESS unit and the shipping flat.
- The BESS is elevated with hand jacks and dunnage at the barge landing to protect it from the potential floods.
- November site preparation for BESS continues.
- Unusually warm Fall/Winter, sustained wind, rain, flooding and unseasonably warm, above freezing temperatures (40 F + into January 2014). Cannot move Bess from barge landing for installation.

- Access road from barge landing area to installation site, too soft for heavy equipment. Temperatures remain above freezing until mid January.

2014

- Storm related electrical distribution issues resulting in multiple power outages.
- January wind Turbine #2 experiences a gear box casing failure. Leaving 4 operational turbines.
- February The BESS is in position, moved from the barge landing to site. Installation of three phase power connections, and fiber optic communications completed. Diesel Unit #3 a JD 6090 generator failure. The unit remained down for repairs until May.
- March generators #1 and #4 experience various mechanical issues. Hoses, water pumps, voltage regulator, actuator arms in radiator room. The Utility has fuel spill. One 6090, generator #2 is operational in the powerhouse.
- March 25 BESS commissioning begins onsite with ABB, LG Chem, Frontier and IES.
- April BESS Equipment Commissioning completed. Work continues with Kwig to repair gensets and synch diesel off transitions
- April 10 a wind farm conductor fails in the conduit on the riser. Wind farm becomes inoperable. No wind power, BESS operation held up for repairs.
- April Engineering, design, procurement and scheduling of feeder repair.
- May 14 Gen#2 (JD 6090) fails due to injector and ECU. Generators #1 and 4 running the village.
- May 17 Wind farm feeder repair completed. Trenching in the permafrost soils to uncover repair the failure point.



Fig. 1 Wind farm feeder repair

- Redesign of the riser conductors to eliminate future failure.
- May 20 the project restarted with low wind input levels.
- Distribution voltage spikes diagnosed as related to school construction. As generator repairs and wind is available, battery system is observed and tuning changes are made.

- June the BESS is disabled until diesel generator repairs are completed.
- August 12 Village goes dark; the battery chargers in powerplant fail to recharge the generators batteries and supply control power to the switch gear. Village suspects BESS fault. IES diagnoses issues and assists Kwig in obtaining new starting batteries and chargers. BESS is disabled.
- August 22 Gen#2 fails due to injector issues, #1 and 4 running the village. BESS disabled due to unreliable diesel plant.
- September the new school is coming online. The base load increase and large motor starting issues are causing outages. Average daily peak loads exceed 250 kW, a 25% increase. Large school pumps starting every 20 minutes and causing village wide distribution related outages. BESS operation discontinued. The new school's base load far exceeds the ability of any one generator in the power house to handle the load causing utility to parallel, two of three operating units.
- September Kwig power house in a weakened state, with generator 1 and 4 holding the village and school utility building running to keep the water plant going. Generator mechanic has been scheduled for two weeks. BESS disabled until October.

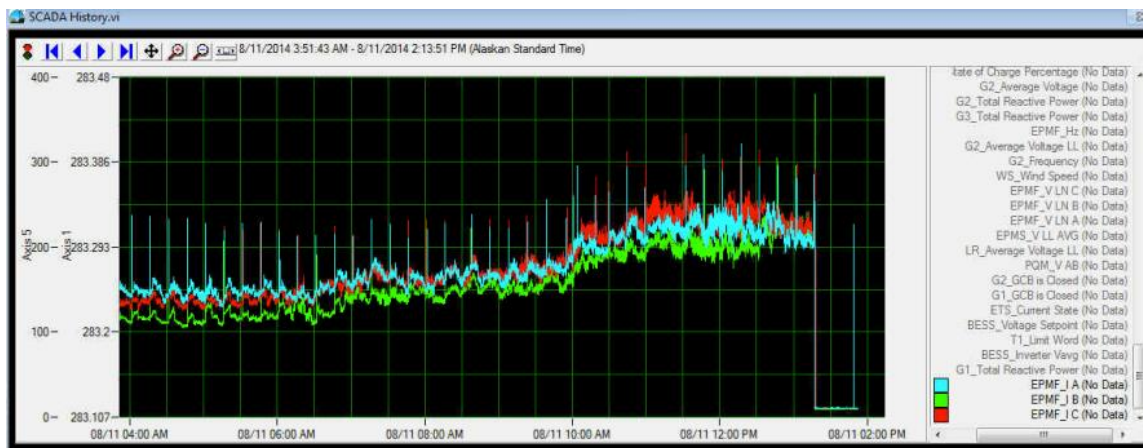


Fig. 2 SCADA diagnosis of Amperage spikes from school motor

- September 25 install additional SEL 735 power quality meter at the Bess to insure power quality and improve diagnostic capability. The figure above is a graph of distribution feeder spikes measured on the main distribution feeder to the school. After the metering was installed, it was demonstrated that these spikes, which were occurring every 15 minutes, were related to the pumps in the school. The school pumps starting issue required some time and effort to diagnose, and demonstrate that outages were not related to the wind system or the BESS. IES worked with local technicians the school district and school design engineers to collect and diagnose school power issues.
- October 22 VFDs are installed on the School's pumps to control the inrush current spikes. The BESS is re-enabled.
- October 25 a seagull caused a fire at the wind farm BESS power pole. BESS disabled until pole is repaired.



- November power pole repairs completed, autonomous wind-battery-diesels off events resume. Thru January 2015.

2015

- January Diesel genset failure in Kwig power house. Autonomous Wind BESS operations discontinued, until diesel plant is operational.
- February Restored diesel plant operations, BESS enabled.
- April Data collection computer disk failure. Replacement unit shipped to site and installed by KPC. Failed unit sent to specialist for data extraction.
- May Kwig Site visit by AEA project manager and ACEP representatives.
- June – December Continuous autonomous operation, when diesel plant is operational. 7months of operations

2016

- January,-May restricted continuous autonomous Wind- BESS when diesel plant is operational.
- July – August BESS module high temperature alarm. Failed ventilator actuator arm, needed to cool BESS in warm weather summer. Local operators replace, approximately \$200, plus time to diagnose.
- September a new 6090 genset installed in the power plant, resume autonomous BESS operations
- October 2016 BESS DC contactor replaced by IES and KPC technicians. BESS down approximately 2 weeks.
- October Continuous autonomous operation for the BESS.
- December Diesel replacement in power house continues, a new larger genset installed.

Kwigillingok Hybrid Wind-Diesel-BESS: SCADA/Modeling Results

June 2015

Dennis Witmer, Energy Efficiency Evaluations

7-27-2015

Abstract

A high penetration Wind-Diesel-Energy storage hybrid system is currently operating in Kwigillingok, Alaska. During June 2015 this system operated continuously without any operational issues. This brief report compares the operational data collected by the installed SCADA system with model results, important to validate the model.

Description of system in Kwigillingok

Kwigillingok is a remote village in Alaska, and has no connection to roads or electrical grids. Beginning in the 1970's, residents of Kwigillingok were provided electrical power by diesel electric generators, with an annual load of about 1,185,025 kW-hours, or an average of 135.3 kW (2013 PCE). In 2012, five Windmatic 17S turbines were installed in the village, each with a peak power rating of 95 kW, for a total installed capacity of 475 kW, or an average of 350% of the load. During strong wind events, the wind farm is capable of providing more electrical energy than the village requires for the electrical load. This system is properly characterized as a high penetration wind diesel hybrid system.

There are several strategies for dealing with the excess energy. In other Alaskan communities with somewhat smaller installed wind capacities, the diesel generator is maintained at some minimum load, usually about 20% of the rated generator power, while the excess wind energy is either dumped to a load reducing boiler (which can rapidly follow changes in wind power) or the wind turbines are "curtailed", meaning that the power extracted from them is reduced to more closely match the load. While this results in a stable electrical power generation system, it does not extract maximum benefit from the installed wind system.

In Kwigillingok, two additional components have been added to the system: a battery electric storage system (BESS) at the community level, and a group of electric thermal storage stoves (ETS) in individual residences, both new technologies in the initial demonstration phase. The goal of operation of this system is to increase the renewable wind penetration by 1) allowing stable operation of the electrical system with diesels off operation during wind events, using the BESS to fill in the frequent lulls in the wind power, and 2) using the ETS units to absorb additional available wind energy to displace home heating fuel. Modeling conducted as part of this project proposal indicated that using these two technologies could roughly double the diesel fuel savings at the power plant while providing significant heating fuel costs for local residents.

The idea of using batteries to permit high penetration wind systems for remote communities in Alaska is not new, given that such a system was installed in Wales in 1997, using Ni-Cad Batteries and a rotary converter. However, the weak link in these systems has always been the batteries, as Ni-Cad batteries are expensive, and lead acid batteries are rapidly degraded by deep cycling and rapid charge discharge, and must be replaced with depressing frequency. Recent advances in Lithium Ion batteries intended for the electric car market may have changed

the equation: these batteries are capable of much higher charge/discharge rates, and can survive for many more deep cycles.

The BESS system installed in Kwigillingok is a “first of a kind” demonstration project, funded through the Emerging Energy Technology Fund. As is true for all “first of a kind” projects, some aspects of this project have taken longer than hoped, beginning with the delivery of the unit to the village (delayed by 6 weeks by barge schedule, further delayed by several months by weather preventing the move from the barge off-loading area to the village), problems with integrating the BESS unit into the local electrical system, and further issues with the generators at the village electric utility plant. These issues occupied much of calendar year 2014.

However, many aspects of this project have gone extremely well, beginning with the selection of the BESS supplier, and their use of batteries from the current world leader in the production of Lithium Ion batteries for vehicle applications. Initial commissioning of the battery system in July 2014 was completed, with the BESS performing as expected. However, some issues remained, especially with regard to the transfer of control between the BESS system and the DEG, a systems control issue. Some delay occurred in solving this issue due to multiple failures in the diesel plant, which needed to be resolved before the demonstration could continue.

In this demonstration project, the stated goal has been to test the use of energy storage in a village system, and to understand how these systems work. Modeling has long been understood to be an important part of analyzing the performance of hybrid systems, and commercial models such as HOMER have been used to evaluate the integration of renewable power with diesel generators. However, HOMER is intended as an economic screening model, requires a full year of load and resource data, and has a time step size of no smaller than 1 minute (reduced from 10 minutes only in 2015).

The model used in this study had its origins in the analysis of laboratory data of fuel cell and battery systems, where experiments lasted from a few minutes to a few days. The goal of modeling was to evaluate electrochemical performance, system losses, and overall efficiency of these systems. Eventually it became apparent that including integration with diesel engines was essential for understanding how these systems could be integrated into Alaska village power systems, as well as incorporating the highly variable renewable energy from wind or PV. Initial studies focused on the performance of such systems during relatively short term wind events (watching a battery charge and discharge over time).

The ultimate question of “is this system better than straight diesel” involves an economic analysis, which was also incorporated into the model, albeit in a relatively straightforward way—the model calculates a baseline diesel plant cost (capital, O&M, and fuel costs) and compares that to the total cost of the hybrid system (diesel, wind, storage; capital, O&M and fuel). This model does not incorporate renewable energy incentives like tax breaks. In addition, the value of heat, both heat recovered from the diesel gen sets and heat generated from excess electricity can also be calculated. This can be done for any data set over any time period.

Validation of a model is critical to the acceptance of the results from that model. One way of validating a model is to compare it to an accepted model. Over the past few years, the model used in this study has been run against HOMER, and has provided identical results (within rounding errors) when care is taken to provide exactly the same inputs. (HOMER does have some quirks, like converting a diesel efficiency curve to a linear estimate—which works fairly well for most engines, but not all).

The other way of validating a model is to compare it to field data. In Alaska, HOMER has been used to estimate wind power production over an annual basis, which can then be compared to reported annual wind production reported to PCE. Doing so reveals that actual wind production historically has been well below the levels predicted by HOMER. In addition, actual project installed cost often exceeded the estimates used in initial modeling. The combination of these two facts has resulted in a loss of enthusiasm for wind projects in Alaska.

The difficulty in comparing initial modeling efforts is that things may change. In the case of Kwigillingok, several major changes occurred between the project proposal time and the installation of the battery system. Major changes include: the increase in average village load from about 135 kW to about 190kW (a 40% increase in load) and the long term outage on one of the wind turbines, reducing the wind input from 5 to 4 turbines. Both of these changes have resulted in a lower than anticipated total energy displacement. However, the data can still be used to validate the modeling efforts.

This report summarizes data collected in Kwigillingok in June 2015 by IES, and compares the observed system behavior with that predicted by modeling. The model requires 3 time step variables: village load, wind speed, and ambient temperature. The model then applies these inputs to diesel efficiency curves, wind turbine power curves, and battery performance curves to estimate the energy flows in the system. The results from modeling can be compared to data collected by the SCADA system from the village. Several simple metrics can be used to assess the accuracy of the model: total kW-hrs of energy produced by the wind, number of diesel start-stop cycles, the amount of time the diesel engine is off, and the total number of gallons of diesel fuel consumed during the time period. Several of these metrics can also be cross checked with other measurements, including the total billable kW-hrs during the month, and the daily fuel transfer logs from the power plant.

Hybrid configuration in Kwigillingok, Alaska, used in modeling.

Diesel Generator

The Kwigillingok power plant has a total of 4 diesel generators, but in June 2015, almost all the diesel power came from G2, a John Deere 6090, rated at 275 kW. This engine was set to operate at a minimum power level of no less than 65 kW. Maximum village load during the month was 230 kW, and

a minimum of about 75 kW so this single generator was capable of meeting the electrical needs of the village for the entire month. For modeling purposes, a single diesel engine based on factory nominal fuel consumption curves was initially used, but a second fuel consumption curve was generated based on field fuel flow data. The diesel fuel curve is critical in the modeling, as it defines the base case, and therefore the fuel savings achieved by the hybrid system.

Wind Turbines

Five identical Windmatic 17S turbines have been installed in Kwig, although only 4 units were operational during June 2015. Power Productions curves for the turbines were provided by IES, but are virtually identical to the Windmatic 17S curve available in HOMER.

Lithium Ion Battery Energy Storage System

A first of a kind lithium ion battery was installed in Kwigillingok during 2014. This system uses LI batteries supplied by LG Chem, one of the major producers of LI batteries for the emerging electric car automotive market. The inverter integrated with the batteries was provided by ABB, a very experienced supplier of robust inverter packages.

The model used electrochemical performance provided by the battery supplier, along with an inverter loss factor proportional to energy flow.

Electric Thermal Storage and Other Secondary Electrical Loads

The High Penetration Hybrid Wind Diesel System designed for Kwigillingok was intended to be a 300% penetration system, meaning that the nameplate ratings of the installed wind turbines was three times greater than the average load (475 kW vs. 135 kW), and was designed to use excess electricity for heating loads. In lower penetration systems, centralized load reducing electric boilers can be placed on a centralized heat loop intended to also distribute waste heat from the diesel engine, but constructing, operating and maintaining these loops adds costs to the system. Adding distributed thermal loads in the form of electric heaters for residences uses existing infrastructure for utilizing this excess energy, and adding storage allows this heat to be smoothed and used after the end of the wind event. These Electric Thermal Storage (ETS) units are also equipped with high speed sensors that allow the units to quickly sense the availability of excess power, and switch on and off quickly, allowing them to act as a dispatchable load. Kwigillingok has both a load reducing boiler and ETS units installed.

Heat loads are driven mostly by ambient temperatures—the colder it is outside, the more energy required to heat a space—and not directly connected to electrical loads. This complicates calculation of the value of “free heat”, either from the diesel generator or excess wind energy—heat energy is only of value if there is a need for it—ie, in the summer months there is no demand for heat. In the modeling efforts for Kwigillingok, heat demand was assumed to be proportional to the temperature and the size of the space to be heated, both for heat available from the diesel generator and from excess wind.

System control strategy

Control strategy for the baseline diesel case is simple: a diesel electric generator is operated to meet the electrical load of the village, and waste heat is provided to heating loads as available and needed. Adding a small amount of wind power reduces the demand for diesel generated power, and reduces the heat generated.

Adding more wind power leads to situations where the wind can provide most of the energy for the village during wind events, but diesel engines must remain on to provide energy during lulls in the wind. Given that operating at loads below 20% can lead to maintenance issues, systems are operated with this minimum load on the engine. This leads to the need for either limiting the output from the wind turbines (curtailment) or the use of load reducing boilers. The inability to go to “diesel’s off” operation limits the amount of diesel fuel that can be saved at the power plant, and limits the value of the installed wind turbines.

Adding more wind power with electrical storage and permitting “diesels off” operation allows for greater displacement of energy, both at the power plant and for heat loads.

Given that displacing a kW-hr of electricity is more valuable than displacing a kW-hr of heat (due to the lower efficiency of diesel generators as compared to an oil burning heater), the highest value of wind power is to displace as much fuel at the power plant as possible. For this reason, as wind power production rises, the model is designed to use the first available excess wind to charge the battery, leading as quickly as possible to a diesel’s off state. Only when the battery is full, or the total available power is greater than the battery can absorb, will energy be sent to heat loads.

However, the control system in Kwigillingok is configured differently, where it appears that initial excess wind energy is first sent to the load reducing boiler before battery charging begins. This leads to some differences between the modeling results and the field data, which will be discussed below. Some further effort is required to reconcile these differences, but even with these differences, the correlation between the model and the field data is very strong.

Conditions in Kwigillingok, June 2015, Model inputs

Village load profile for Kwig, June 2015

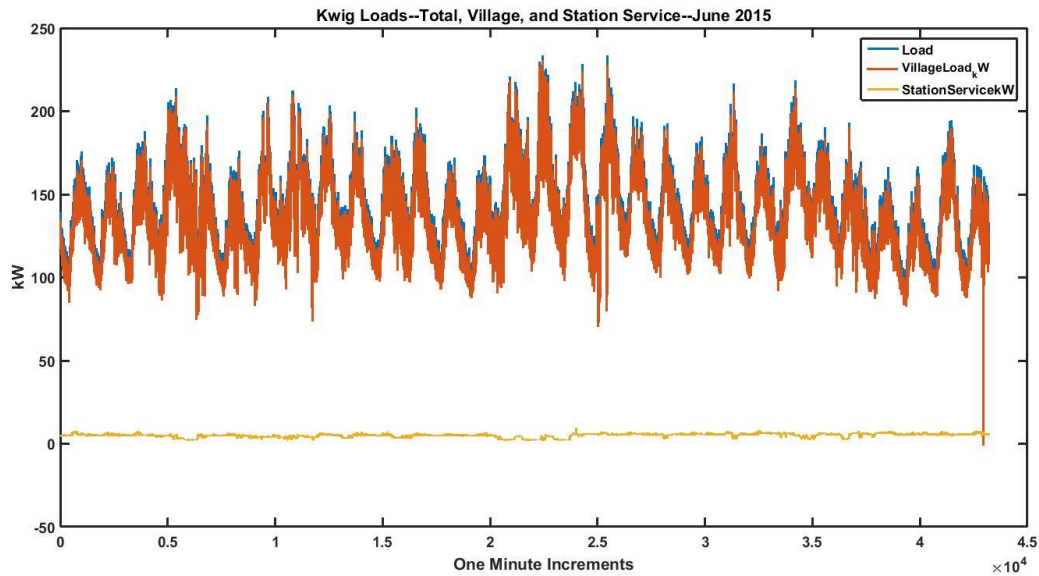


Figure 1 Electrical load measured in Kwigillingok, June 2015. Lower line is for station service, upper line represents village load, and village load including station load (total load on generator). This data series is used in modeling.

Wind Speed in Kwig, June 2015

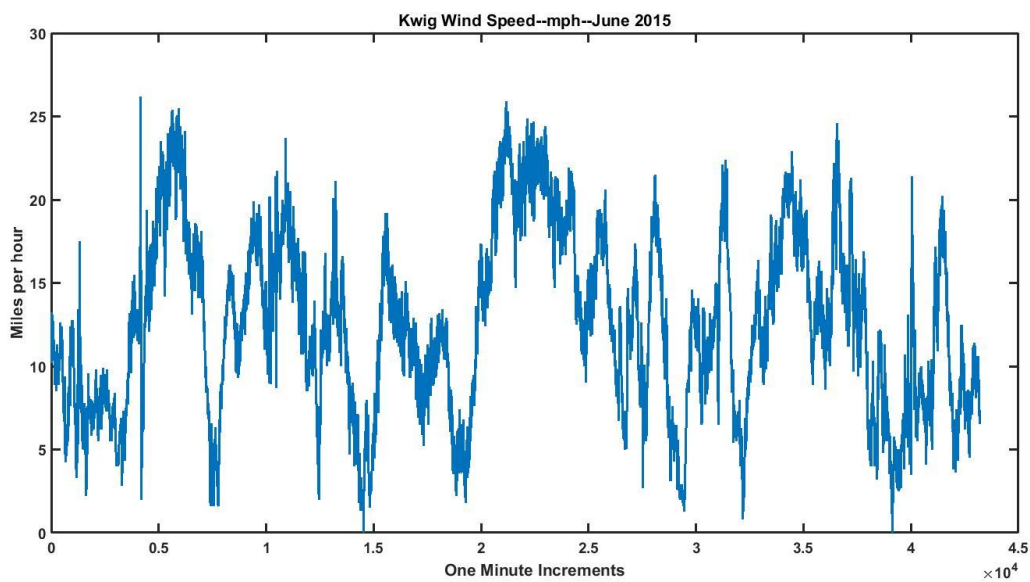


Figure 2 Wind speed, measured at weather station, approximately 2500 feet from wind farm. This wind speed is used in modeling.

Ambient Temperature in Kwig, June 2015

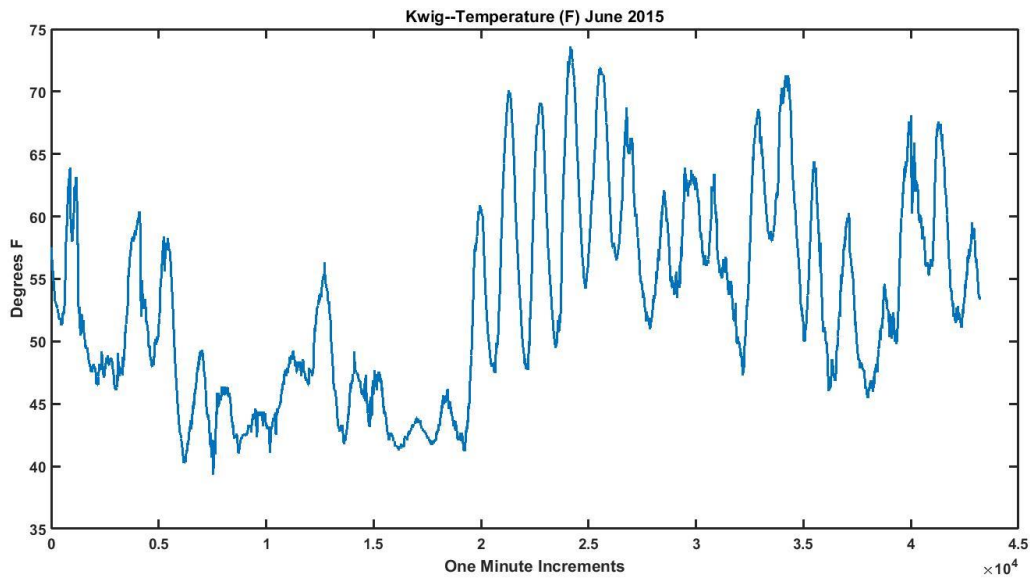


Figure 3 Ambient temperature in Kwigillingok, June 2015. Note the temperatures during the last half of the month are quite moderate by Alaskan standards, and resulted in a request for turning off thermal loads. This temperature is used in modeling, both to calculated air density changes, and to estimate heat loads.

SCADA and Modeling Results:

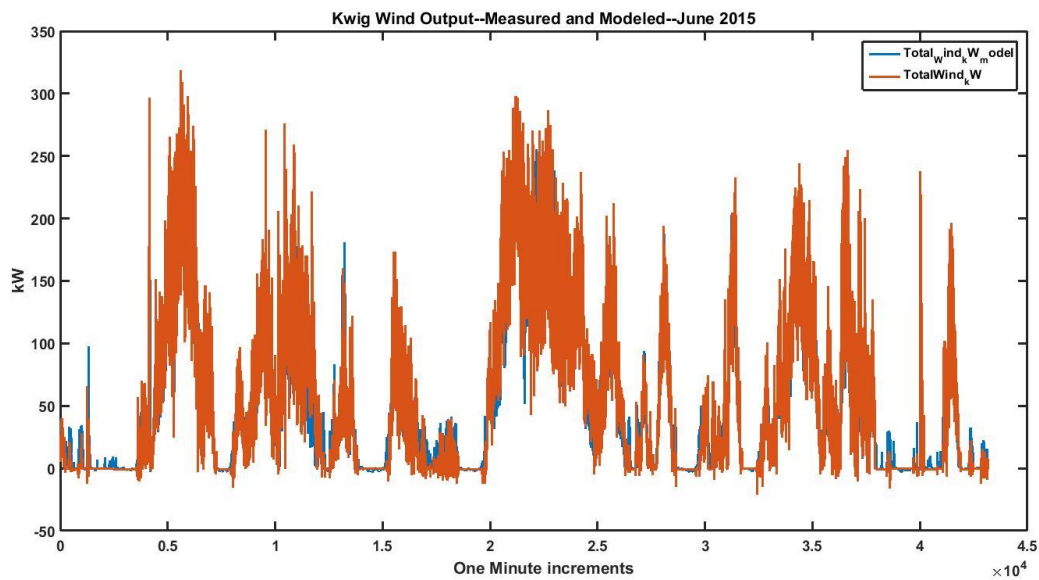


Figure 4 Measured total wind production vs wind production calculated based on wind speed, temperature, and nominal wind power curve for 4 Windmatic 17 S turbines. Note very close correlation between two curves. No hub height correction.

Diesel Generator loads, Kwig, June 2015

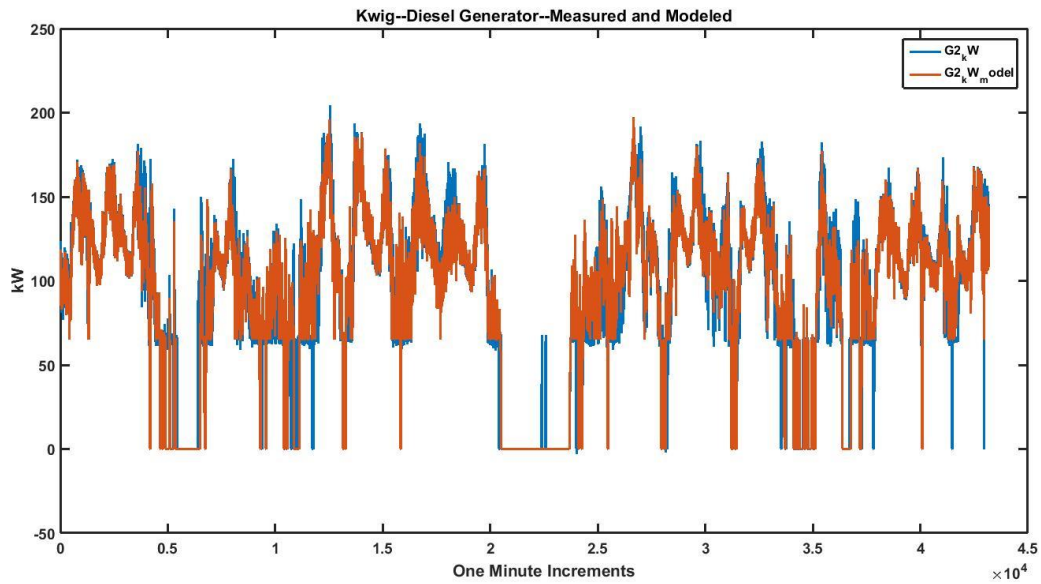


Figure 5 Generator Loads in Kwig, from SCADA and model. Note extended diesel's off periods corresponding to strong wind events. Note some minor differences between SCADA data and model, but overall strong correlation between them.

Detail of SCADA data from first wind event.

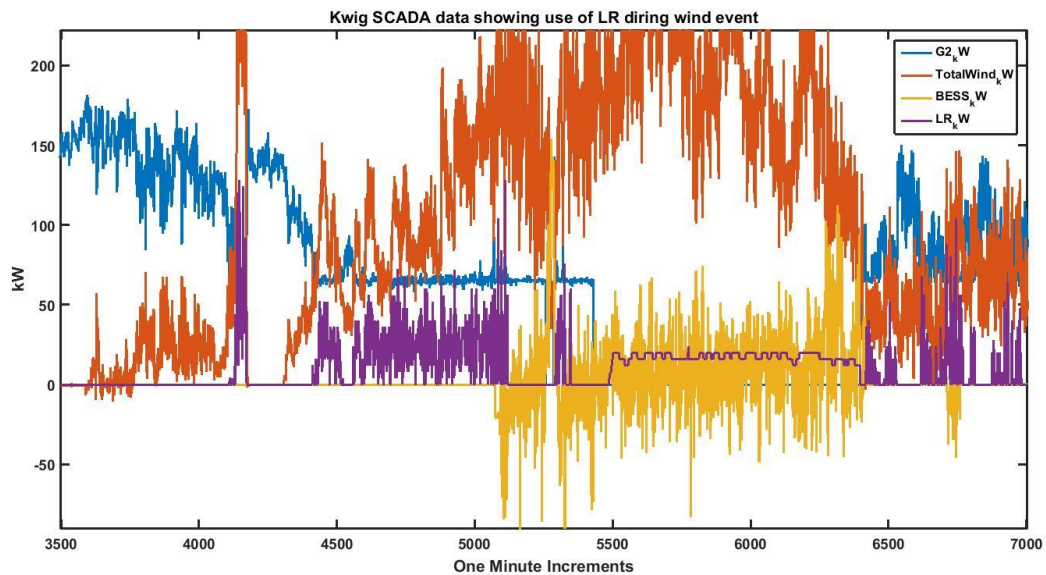


Figure 6 SCADA data (detail) of first wind event. Note use of LR to balance wind before battery use begins. Also note extended diesels off period during strongest wind. (Battery charging shown as negative) =-].-/-9

Model data from same event

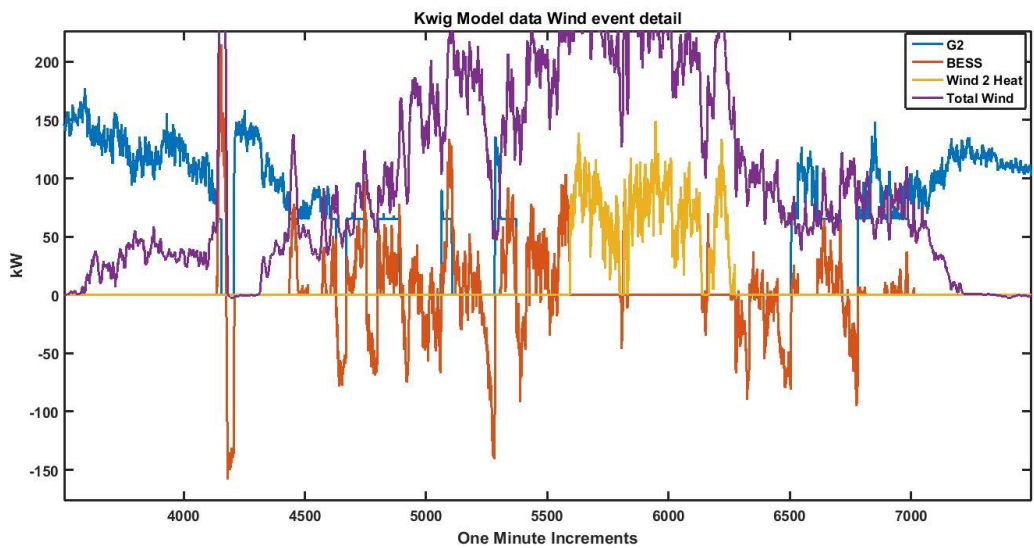


Figure 7 Model data from same wind event as figure above. Note that diesels off operation is achieved more quickly, and that energy is diverted to heat only after battery charging takes place (Battery charging shown as positive energy)

Table 1: Comparison between SCADA and Model results

	SCADA	Model	
Total Diesel load	101335	101336	(4)
Total Wind Produced	37,818	37,564	kW-hrs
Wind to village load		33,366	kW-hrs
Diesel Stop-starts	31	33	
Diesels Off time	106	120	hours
Total Diesel fuel	5786	5732	(1) gallons
Baseline DF		8417	(2) Gallons
No Storage DF		6487	(3) Gallons

Note 1: Total Diesel fuel sum of G2 fuel flow, model from empirical curve

Note 2: Baseline from empirical curve

Note 3: Model run results with BESS off

Note 4: Village load + Station Service load

Power Quality

Power quality data was collected at 1 second resolution for analysis of frequency and voltage stability, along with a power quality meter capable of recording out of range events at 1000 Hz. One second data indicated that at all times frequency remained between 59.9 and 60.1 Hz, and voltage was between 475 and 485 volts. This includes the 31 diesel start/stop events, and shows that the system is stable in all system states, and during transitions between states.

Discussion and Conclusions

- High penetration wind-diesel-energy storage system in Kwigillingok is working—diesel start/stops occurring without operator control, excellent power quality through all operating states.
- Model of system indicates close correlation with SCADA data, validating the model.
- SCADA system data indicates a 32% fuel savings compared to baseline diesel operation for the month of June.
- Modeling shows that system without storage would have a 23% fuel savings, indicating a significant increase in fuel savings from addition of storage and diesels off operation.
- Preliminary modeling assuming higher hybrid penetration indicates that fuel savings of up to 50% are possible at power plant.

Kwigillingok BESS Performance

Initial analysis for November 2014

Dennis Witmer

12/17/2014

The “First of a Kind” BESS system installed in Kwigillingok is operational. This report analyzes data collected during a two week period, which includes several wind events that resulted in eight “diesel’s off” events, seamlessly initiated and ended by the utility control system. During this time, wind power provided 31% of the total electrical needs of the village, as well as providing a modest amount of heat to ETS stoves. Additional effort to improve operation of the diesel plant and repair of one of the wind turbines should result in even better performance in the future. However, the system is working as designed, as the BESS is permitting a much higher wind penetration compared to other remote wind-diesel systems.

High Penetration Wind Diesel Operation in Kwigillingok, Alaska

November, 2014

Initial Analysis

December 17, 2014

Description of system in Kwigillingok

Kwigillingok is a remote village in Alaska, and has no connection to roads or electrical grids. Beginning in the 1970's, residents of Kwigillingok were provided electrical power by diesel electric generators, with an annual load of about 1,185,025 kW-hours, or an average of 135.3 kW (2013 PCE). In 2012, five Windmatic 17S turbines were installed in the village, each with a peak power rating of 95 kW, for a total installed capacity of 475 kW, or an average of 350% of the load. Obviously, during strong wind events, the wind farm is capable of providing more electrical energy than the village requires for the electrical load.

There are several strategies for dealing with the excess energy. In other Alaskan communities with somewhat smaller installed wind capacities, the diesel generator is maintained at some minimum load, usually about 20% of the rated generator power, while the excess wind energy is either dumped to a load reducing boiler (which can rapidly follow changes in wind power) or the wind turbines are "curtailed", meaning that the power extracted from them is reduced to more closely match the load. While this results in a stable electrical power generation system, it does not extract maximum benefit from the installed wind system.

In Kwigillingok, two additional components have been added to the system: a battery electric storage system (BESS) at the community level, and a group of electric thermal storage stoves (ETS) in individual residences, both new technologies in the initial demonstration phase. The goal of operation of this system is to increase the renewable wind penetration by 1) allowing stable operation of the electrical system with diesels off operation during wind events, using the BESS to fill in the frequent lulls in the wind power, and 2) using the ETS units to absorb additional available wind energy to displace home heating fuel. Modeling conducted as part of this project indicated that using these two technologies could roughly double the diesel fuel savings at the power plant while providing significant heating fuel costs for local residents.

The idea of using batteries to permit high penetration wind systems for remote communities in Alaska is not new, given that such a system was installed in Wales in 1997. However, the weak link in these systems has always been the batteries, as lead acid batteries are rapidly degraded by deep cycling and rapid charge/discharge, and must be replaced with depressing frequency. Recent advances in Lithium Ion batteries intended for the electric car market may have changed the equation: these batteries are capable of much higher charge/discharge rates, and can survive for many more deep cycles.

The BESS system installed in Kwigillingok is a “first of a kind” demonstration project, funded through the Emerging Energy Technology Fund. As is true for all “first of a kind” projects, some aspects of this project have taken longer than hoped, beginning with the delivery of the unit to the village (delayed by 6 weeks by barge schedule, further delayed by several months by weather preventing the move from the barge off-loading area to the village), problems with integrating the BESS unit into the local electrical system, and further issues with the generators at the village electric utility plant.

However, many aspects of this project have gone extremely well, beginning with the selection of the BESS supplier, and their use of batteries from the current world leader in the production of Lithium Ion batteries for vehicle applications. Initial commissioning of the battery system in July 2014 was completed, with the BESS performing as expected. However, some issues remained, especially with regard to the transfer of control between the BESS system and the DEG, a systems control issue. Some delay occurred in solving this issue due to multiple failures in the diesel plant, which needed to be resolved before the demonstration could continue.

This report summarizes data collected in Kwigillingok in November, 2014, in particular, during the first two weeks of the month, when the system operated in an autonomous mode, transitioning between diesels only operation when the winds were calm and a diesels off mode when sufficient energy was available. Unfortunately, this operation was possible with only one of the diesel generators in the plant, and ended when this generator was shut down for needed maintenance. Also note that one wind turbine was offline for the entire month, and so the total wind generation is reduced by 20%.

Description of Data Collected and Analyzed for this report

Data used for this report were obtained from the SCADA system installed in Kwigillingok by IES, at 1 minute intervals. The data analyzed included: Diesel Generator power from G3, Total Wind power, BESS KW, BESS State of Charge Load Reducing Boiler kW, ETS kW, Power Plant load. The interval analyzed was from 1:01 PM on 11/1/2014 to 12:59 PM on 11/15/2014, a total of one minute less than 14 days, or 20159 minutes. The record count for the data set matches the number of minutes, indicating that the record set, as transferred from the SCADA system has one record for each minute in the time period. The Village Load was not directly measured, but can be calculated as follows:

$$\text{[Village load]} = \text{[G3 Total Power]} + \text{[Wind Total Power]} + \text{[BESS kW]} - \text{[LR]} - \text{[ETS]} - \text{[Station power]}$$

Note that this treats the BESS power as negative when the battery is being charged and positive when the BESS is delivering power—in other words, the BESS is considered a generator rather than a load.

However, not all the records in the data set are complete. The Total Wind data appears to be complete (has a number for every record), but the G3 Total Power data includes only 19411 records, indicating that 748 data points were missing for this item, or about 3.7% of the total records. Since the G3 Power is critical for calculating the village load, the decision was made to do a record by record examination of the data set to see if a reasonable estimate could be made for this value to repair the record set. The

criteria for repair was this: if the record was complete except for the G3 power level, a nearby record value was inserted so that the Village load was consistent with nearby records. This means that the G3 power level estimated depended on wind power and BESS power as which can vary considerably, but maintained a consistent village load. A total of 438 records (2.2%) were repaired using this method. The discussion below will not correct for these errors, as the number of records and the error per record are small compared to the overall totals.

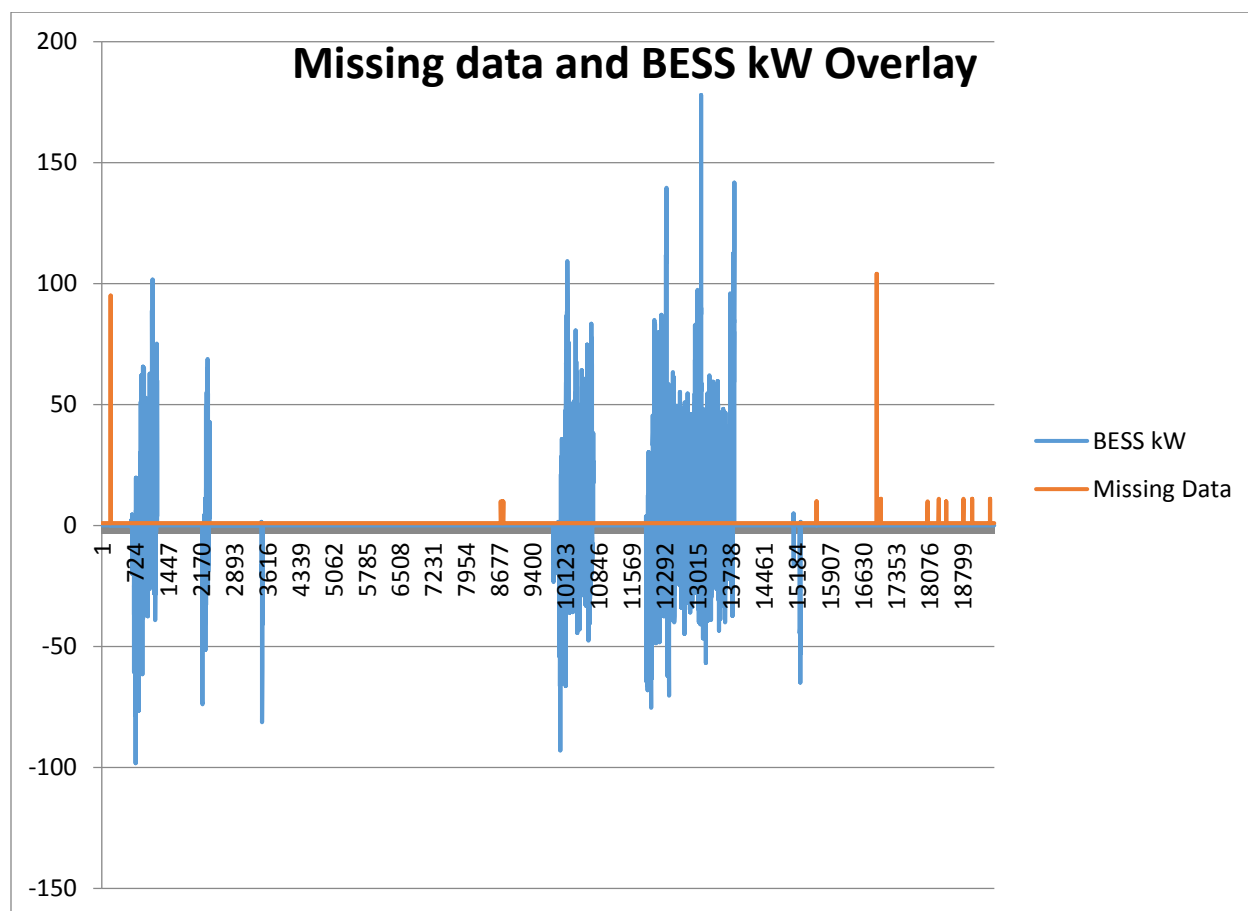


Figure 1 Locations of missing records as compared to BESS activity. X axis in minutes.

However, upon examination, some of the records were not repairable, as these records did not include acceptable values for most of the data points. These defective records mostly occurred in blocks of 10 minutes, although one set of 104 minutes was also discovered, with a total of 310 records (1.5%). These records were deleted in their entirety. Note from figure above that these missing records did not correspond to BESS activity. However, it will result in a slight under reporting of Diesel engine activity, as well as some wind

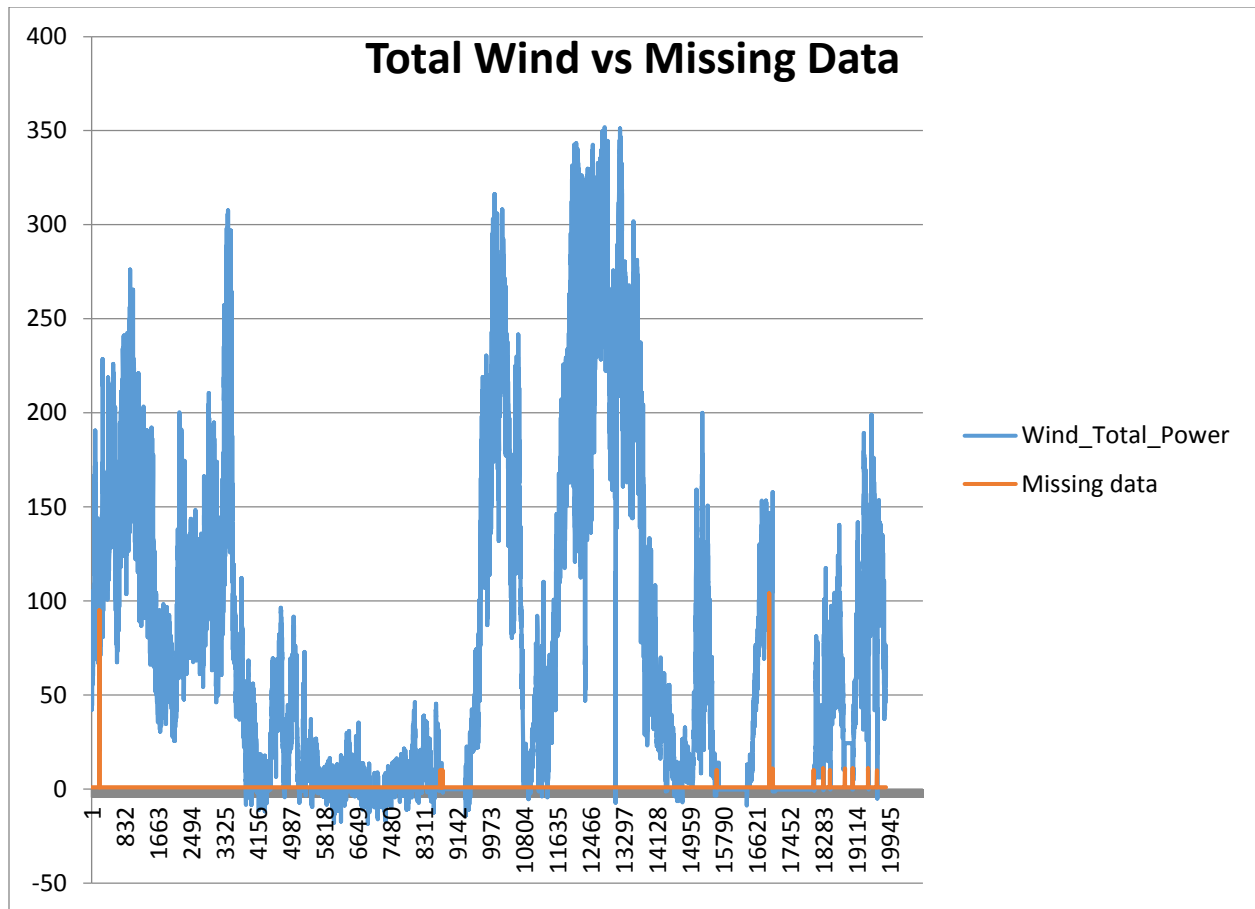


Figure 2 Missing data vs Total Wind Power. Note that missing records correspond to times of moderate wind.

As can be seen in figure 2 above, the periods with missing data correspond to periods of moderate wind, which means that both total wind output and total diesel output will be decreased by these missing records. However, the overall discussion about the relative wind penetration should be unbiased.

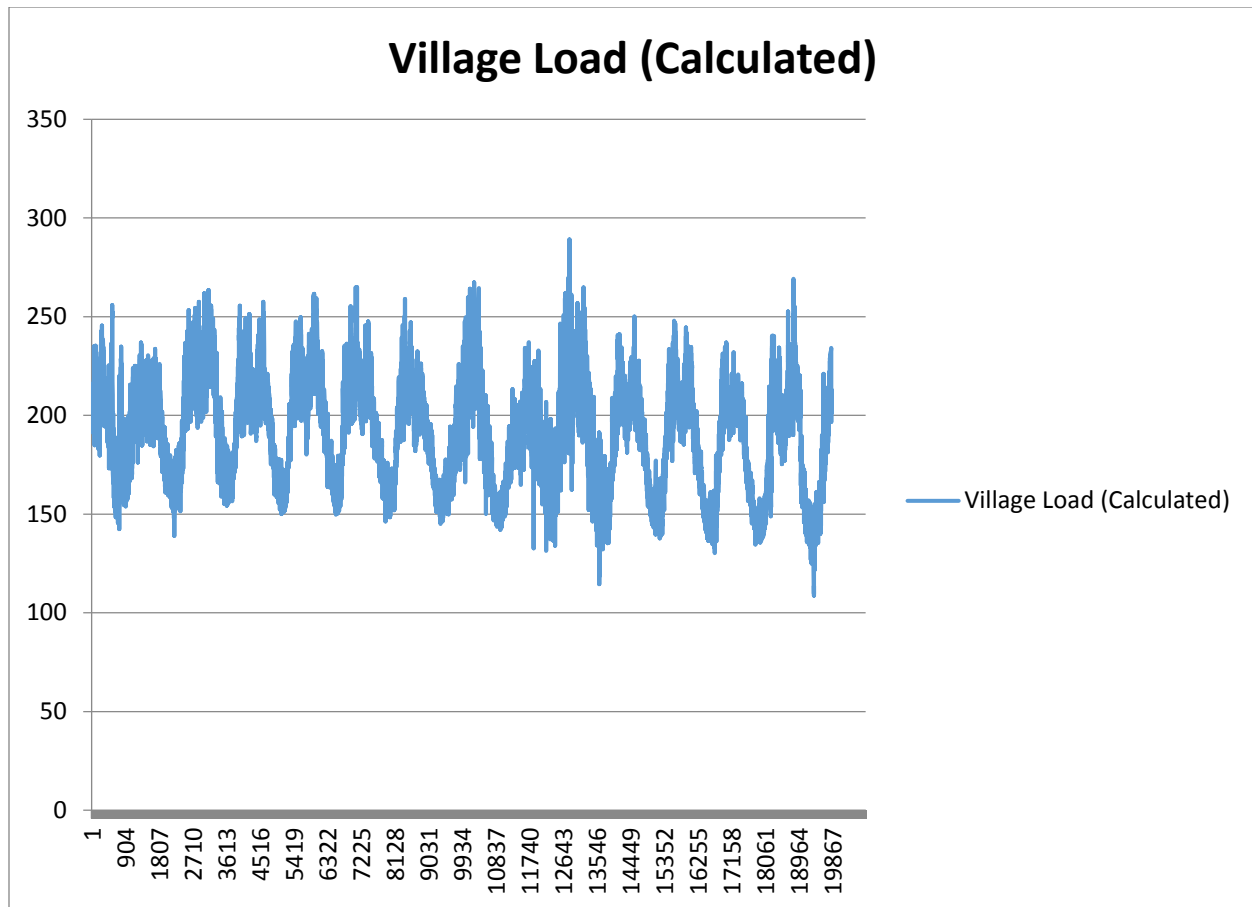


Figure 3 Village load, calculated from generation and loads.

Loads calculated from above formula are show. Note that the chart contains 14 peaks, corresponding to the 14 day period under discussion. Also note that average load is about 191.6 kW, about 60 kW higher than average load reported in the 2013 PCE report. This increase in load is explained at least in part by the construction of the new school currently underway in Kwigillingok.

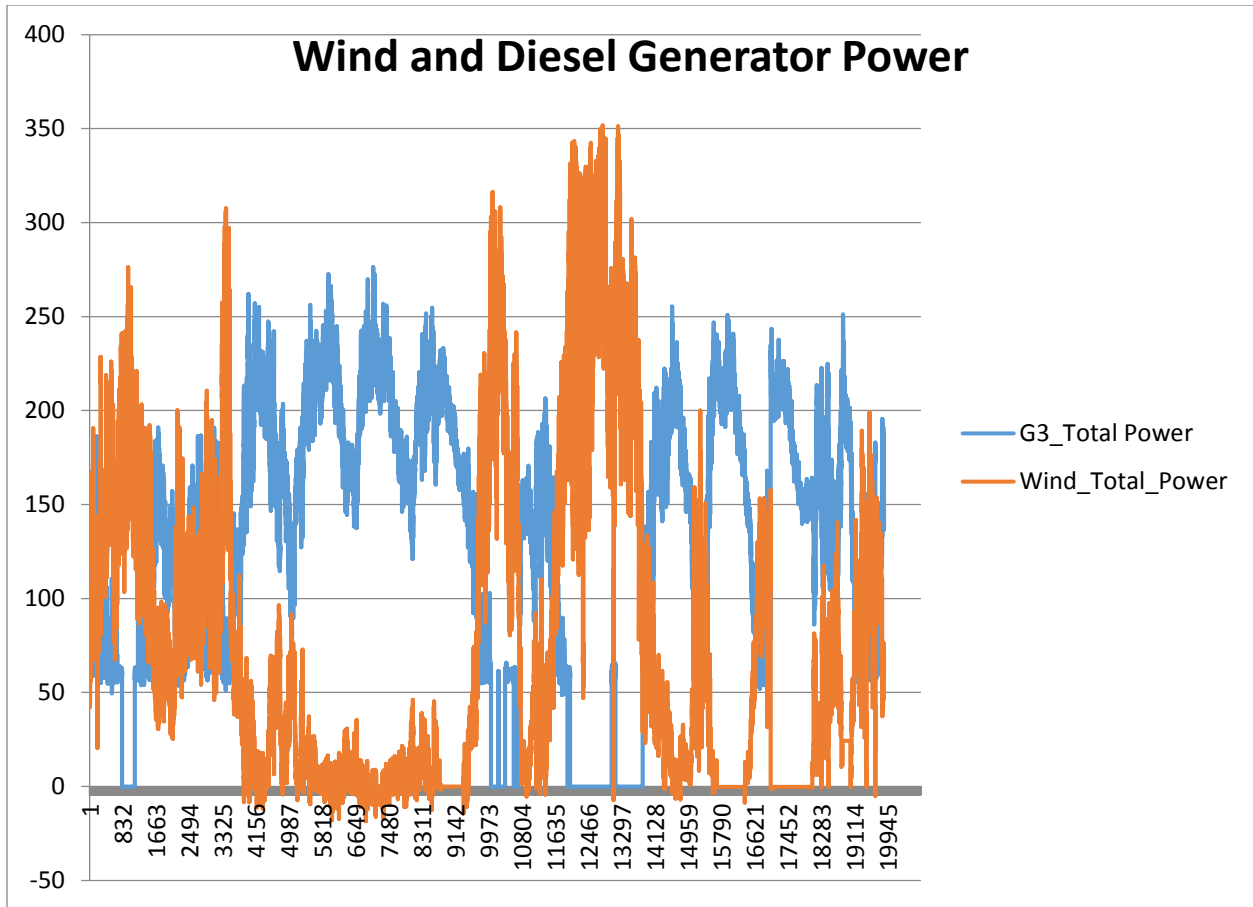


Figure 4 Wind Power and DEG output. Note that during periods of high winds, DEG is off.

Figure 4 above shows a trace of the diesel electric generator output vs the total wind power. Note that during periods of high wind, the diesel electric generator is turned off. Those periods are:

Diesel off	Diesel on	Duration (minutes)
Nov 2, 4:07 AM	Nov 2, 9:26 AM	319
Nov 8, 2:10 PM	Nov 8, 5:13 PM	183
Nov 8, 5:24 PM	Nov 8, 8:01 PM	168
Nov 8, 11:38 PM	Midnight Nov 8/9	22
Nov 9, 12:14 AM	Nov 9, 1:30 AM	76
Nov 9, 10:00 AM	Nov 9, 10:59 AM	59
Nov 9, 11:09 PM	Nov 10, 4:25 PM	1036
Nov 10, 6:02 PM	Nov 11, 5:22 AM	680

Note that this is a total of 8 total Diesel's off events completed autonomously, all completed without causing any recordable power quality events. The total time off is 42 hours, 23 minutes, or about 12.6% of the time during the two weeks.

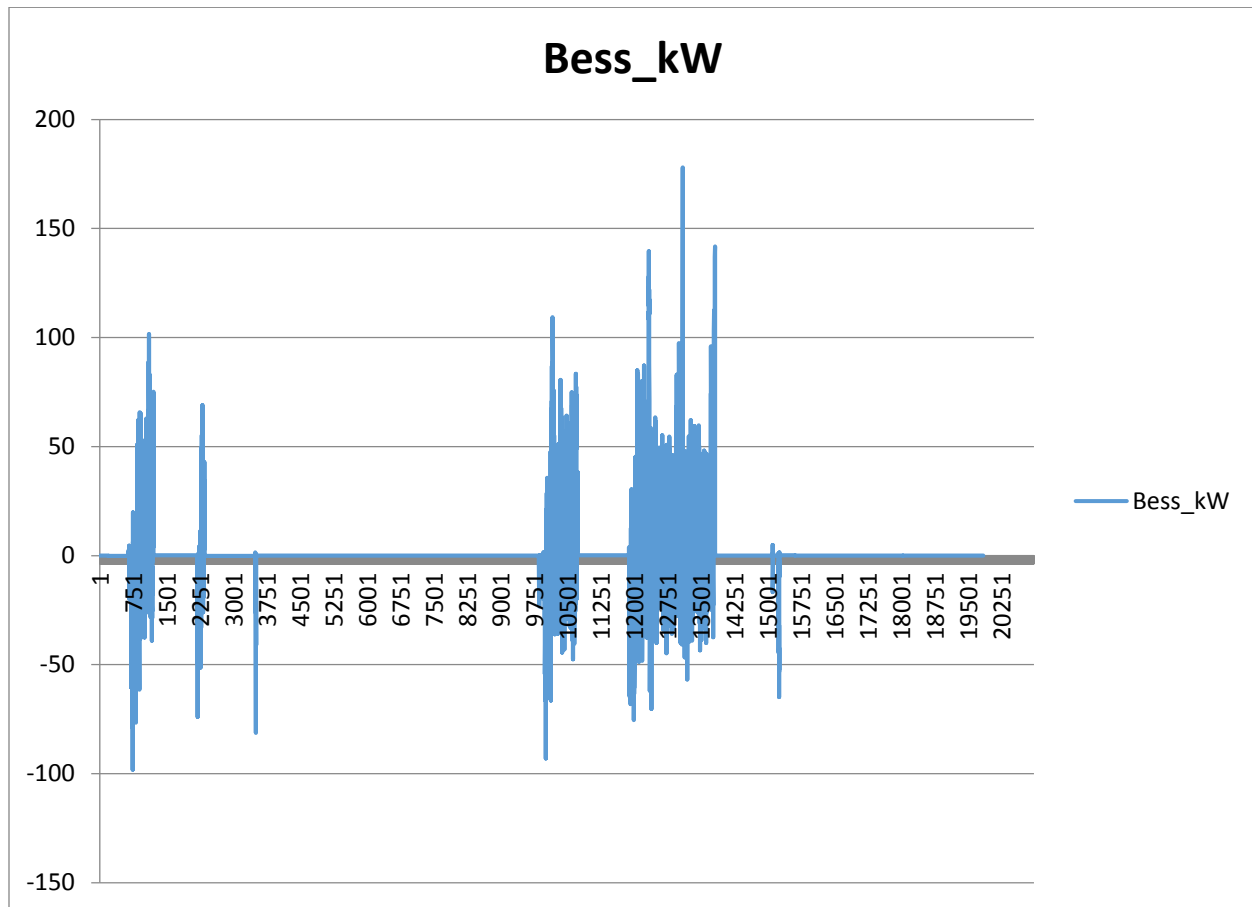


Figure 5 BESS kW. Note that battery experiences many charge/discharge events during each period of activity.

Figure 5 above shows the BESS activity during this period. Note that negative loads correspond with charging the battery, while positive loads are energy delivered to the utility. Maximum charge rates recorded in this data set are about 100 kW, maximum discharge rates are 178 kW.

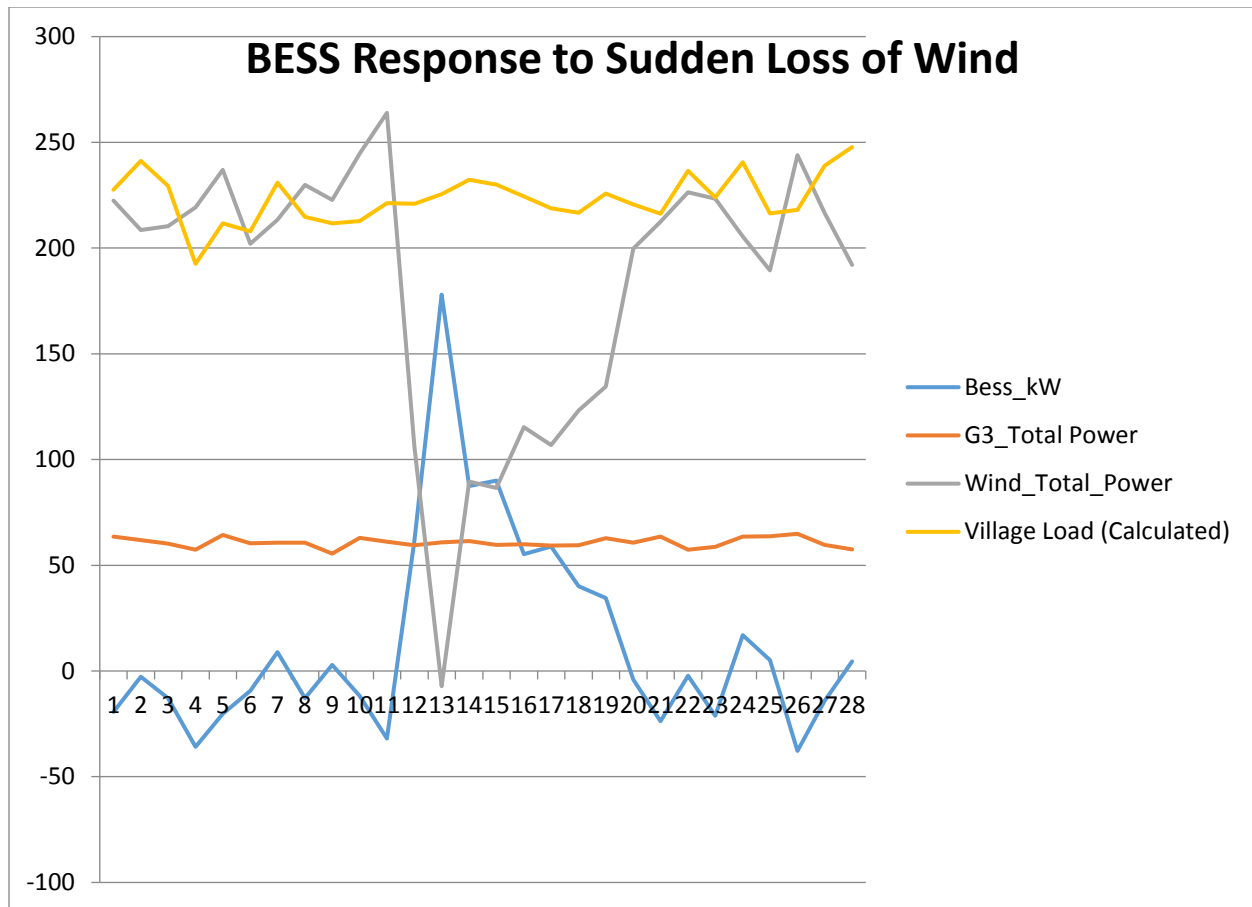


Figure 6 Detail of BESS response to sudden loss of wind.

Note that the BESS responds appropriately to maintain system power during a rapid decrease in wind power.

Energy Balance for 14 day period

Village Load	63417.34	kW-hrs
Diesel Generated Energy	43367.38	kW-hrs
Wind Generated Energy	24601.81	kW-hrs
BESS Power Consumed	-429.12	kW-hrs
EMPS Power Consumed	1688.63	kW-hrs
ETS Power	1675.94	kW-hrs
LR Boiler	1616.40	kW-hrs

Generated power and measured loads balance within about 1.3%.

Discussion and conclusions:

1. The BESS in Kwigillingok is working as anticipated—providing short term firming of wind power during wind events, enabling “diesels off” operation during strong wind events.
2. Automatic transfer between the diesel generator and BESS and back again occurred 8 times during this period without any significant power quality issues.
3. Use of the BESS allowed wind penetration of about 31% of the total village load, with some additional energy used for ETS stoves. The need to curtail wind output was minimized, as appropriate loads could be found for all wind power produced. During both “diesels off” and “diesels at minimum” operation, the BESS provided the flexible load following capability.
4. The BESS proved capable of providing all power needed to cover the village load during one short loss of wind event, as designed.
5. Kwigillingok village power consumption levels have increased dramatically over the past year, due at least in part to the current construction of the new school building. During the 2 week period analyzed in this report, loads averaged 190 kW as compared to 130 kW reported in the 2013 PCE report. This increase in load, plus the fact that only 4 out of 5 wind turbines are currently operational means that the penetration level is about 200%, still a high penetration level, but lower than intended when the project was proposed.
6. As in any “First of a kind” demonstration project, improvements continue to be made in the control algorithms, but basic functionality has been established.
7. Due to aging generators and the increased load noted above, improvements to the village power plant are being undertaken to allow for increased utilization of the automated BESS system.